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THE HIGH PLAINS AND THEIR UTILIZATION

BY

WILLARD D. JOHNSON

U. S. G. S. Twenty-First Annual Report, Part IV

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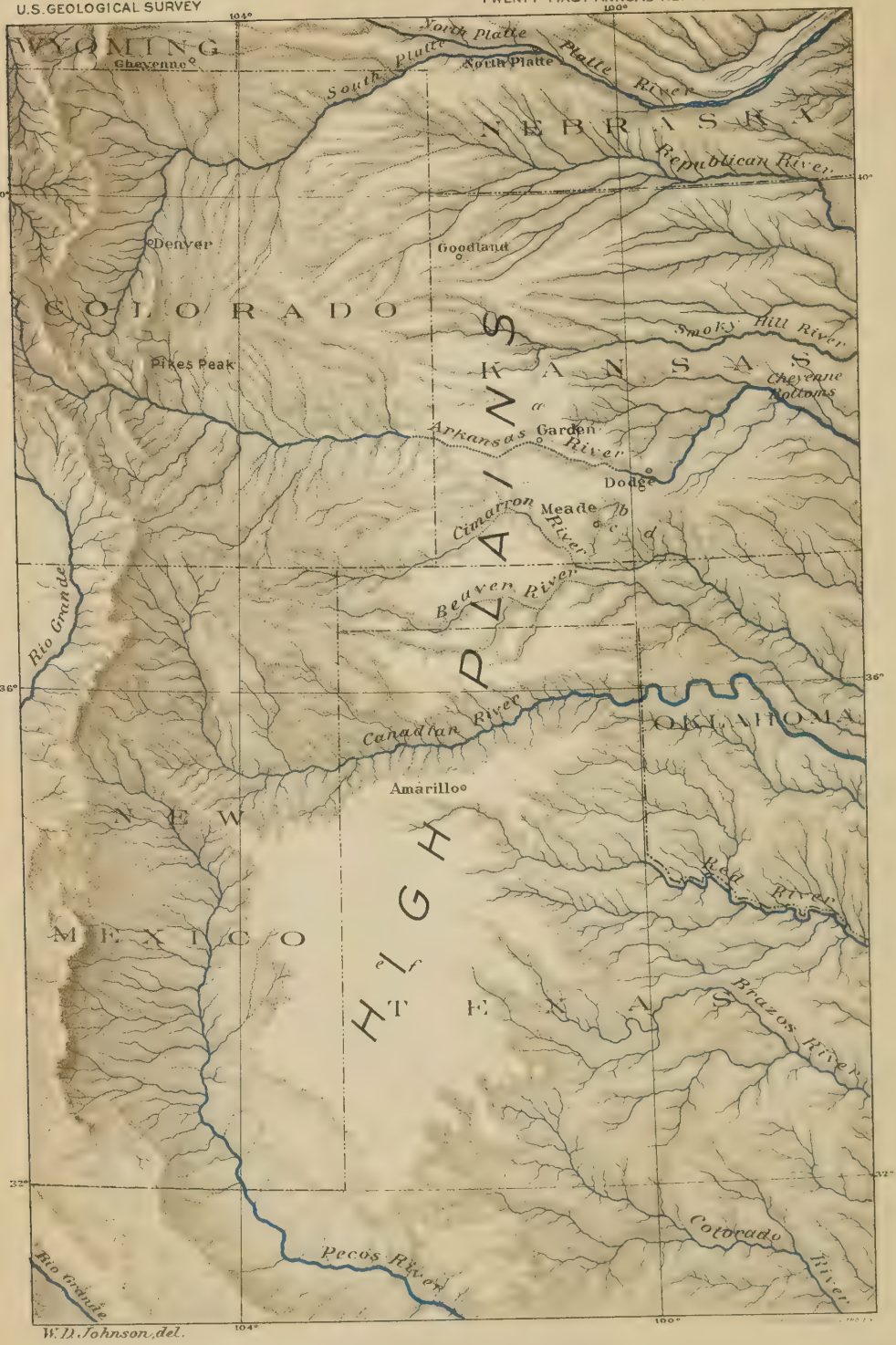


W. D. Johnson, del.

THE HIGH PLAINS

Scale of miles: 0 50 100 150 200

THE HIGH PLAINS AND THEIR UTILIZATION.

By Willard D. Johnson.

CHAPTER I.

INTRODUCTION.

THE GREAT PLAINS AND THE ARID REGION.

The Arid Region, as its limits are now determined, comprises a smaller and much more irregular area than the featureless, "unexplored" region of the early maps known as the Great American Desert. This contraction of boundaries, by the recognition of relatively humid tracts, has in fact gone so far that the name Arid Lands, as implying rather a grouping of detached parts, is coming into use instead.

Originally the desert was assumed to have its beginning in the treeless expanse of the Great Plains, including the whole. We now witness the spectacle of the highest type of agricultural development extended over a belt of States wholly within that early boundary. So much of the Plains had been mistakenly regarded as arid. Yet the development was slow and uncertain. Gradually also, beginning at a somewhat later date, reclamation on a small scale, by irrigation, was undertaken in the unmistakably arid region at the western limit of the Plains, under the spur of the mining development near by, in the mountains. And here, too, natural fertility was demonstrated.

Altogether, however, no great inroad, comparatively, had thus far been made upon this immense body of open land, nor any deliberate effort toward its fullest utilization. The public lands elsewhere had not yet become exhausted. It remained undetermined how far encroachment might profitably be carried without artificial aid. Finally, realizing that exhaustion of public land in the recognized humid areas was close at hand, immigrants rapidly invaded and in a short time covered with settlement the entire intervening space, westward to the zone of irrigation. It was at the worst a drought belt; and the experiment was tried on a scale, and with a reckless elaborateness, that promised heavy disaster in case of failure.

Failure in fact followed, and disaster, with almost complete depopulation, has resulted. Especially was this the case with the High Plains, which presented the maximum inducement of fertile soil and unbroken smoothness of surface.

POSITION AND DISTINCTIVE CHARACTER OF THE HIGH PLAINS.

A TOPOGRAPHIC UNIT.

The High Plains approximately correspond to what is sometimes called, merely for convenience of subdivision, the Central Plains region. They lie in irregular belt form about midway across the long eastward slope of the Great Plains. They have fairly definite boundaries, however, and are in fact a natural subdivision of the Great Plains area.

The Great Plains as a whole constitute a geographic unit. Their extent is so great that they are properly to be regarded as one of the primary divisions of the continent. In that broad sense they are a plain. But topographically they present, in the main, an erosion surface—a surface of degradation—with topographic diversity. That is, in detail they have not, in the main, the character of a plain.

The High Plains are the exception. They have practically no drainage, the local precipitation being disposed of by absorption. Comparatively, therefore, their surface has the general effect of a dead level. Indeed, by way of distinction, they are to some extent locally known as "The Flats" (Pl. CXIV). Of the Great Plains area they are a natural subdivision by topographic difference. In this sense they are a topographic unit.

At the same time they are upland or plateau flats. And they are upland flats of survival; differential erosion of an original vastly extended plane surface has left here a fragment, or a close assemblage of fragments, in relief. The relief is not considerable. It is, however, sufficient to be dominating. But the High Plains—locally so called to some extent also—are individual more because of the conspicuous contrast of surface character they present. They are virtually unscored by erosion; though but a fractional part of the whole slope, they are yet absolutely of great size, and the traveler upon them immediately recognizes that they constitute the Plains proper. They alone have strictly the character which that term implies.

A CLIMATAL UNIT.

The Great Plains area, furthermore, may be regarded as naturally subdivided into belts by climatic difference also. In its westward rise of thousands of feet it passes through climatic gradations from humid to arid. Although, necessarily, along a uniformly rising slope, the passage is gradual, so that any subdivision must be arbitrary, it may at least be said that midway, across a considerable breadth, the climate is semiarid or subhumid. Indeed, the vague Central Plains region is sometimes called the Subhumid Belt. Agreeing generally in position with the topographic subdivision of the High Plains is this subdivision by climatic difference. The boundaries of the topographic belt, to a considerable extent, have been given sharp definition by marginal

THE FLAT UPLANDS.

recession—a work of head-stream sapping and encroachment from the eroded area (see fig. 300)—and the topographic belt in consequence lies somewhat contracted within the limits of the climatic belt; but substantially there is agreement in position. Cause and effect here may appear to be far apart, but it is not difficult to trace their connection. The High Plains are equally the subhumid plains.

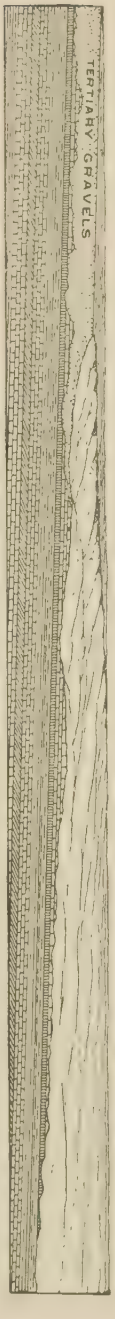


Fig. 300.—Eastern erosion escarpment of High Plains.

THE PROBLEM OF UTILIZATION.

Despite the persistent attempt at settlement already made and its utter and disastrous failure, the High Plains continue to be the most alluring body of unoccupied land in the United States, and they will remain such until the problem of the best means for their utilization shall have been worked out. For not only are they flat and fertile, but their variable annual precipitation, though occasionally falling to the minimum of a truly arid climate, rises to humidity at intervals of about a decade, and may even so continue for two or three consecutive seasons.

It should be recognized at the outset, however, that for agriculture to be profitable in the long run, the subhumid country, like the arid, requires the artificial application of water, though in less degree; and that if the required additional supply is not to be had, the subhumid country in effect is arid also.

It is the purpose in this paper to show that the High Plains, except in insignificant degree, are nonirrigable, either from streams, flowing or stored, or from underground sources, and that therefore, for general agriculture, they are irreclaimable; but that, on the other hand, water from under ground is obtainable in sufficient amount for reclamation of the entire area to other uses; that such reclamation has in fact already begun, and is in process of gradual but sure development; and that it will be universally profitable.

The problem will be found to be essentially one of well making and of the proper location of wells. It is important, therefore, first fully to understand the structure and texture of the ground, to such depths as it may be water yielding; for, given a ground-water supply, upon these factors the "flow," or yield, of wells will wholly depend.

CHAPTER II.

ORIGIN AND STRUCTURE.

Along their eastern front the Rocky Mountains rise from the Plains abruptly, as if from a broadly sloping pedestal. This feature of a far-spread foot slope, made up of their own waste products, is a characteristic of desert mountains. The ranges of the Great Basin region of Utah and Nevada, for example, all have the inclined débris plain as an invariable topographic accompaniment. With such wide sweeping slopes on either hand the desert range has the appearance of being perched upon a base appreciably above the general level. In end view the pedestal effect is conspicuous.

The Great Plains are of such vast dimensions, it is only in imagination that they can be regarded as a foot slope of the Rocky Mountains. However, in the sense that, superficially, ranging down to several hundred feet in depth, they have been built to a smooth surface by mountain waste, stream-spread to great distances, they have this character. At the base of the mountains the Plains mass has a thickness, to sea level, of several thousand feet. It is made up in the main of marine-rock sheets with a general inclination eastward, due to broad regional tilting, in which plains and mountains have shared together.

But the present surface grade of the Plains is not that of the original tilting. The surface has undergone a series of transformations. These have all been accomplished by the eastward-flowing streams from the mountains. In a first stage the mountain streams, traversing the Plains, cut into their smooth structural slope and produced a topography of parallel broad valleys and ridges. In a second stage they ceased to cut, depositing instead, and refilling the valleys they had excavated, even burying the intervening ridges, to a smooth upper surface. The original surface was a product of deformation, the second of a destructive process of stream erosion, the third a product of stream deposit and construction, involving the spreading of a waste sheet to great distances and a uniform level, and to a depth over the greater valleys often of several hundred feet. In the final and present stage, virtually the same streams have returned to the earlier destructive habit, and erosion has in large part carried away the high-level plain of stream construction. About midway of the long slope, in a north-south irregular belt, large uneroded fragments of the smooth constructional plain remain. As we have seen above, these fragments constitute the High Plains.

THE DÉBRIS APRON.

The foot slope of the desert range is a wash plain of mountain waste, burying its foot, in fact. In humid lands the waste from mountain degradation does not accumulate in this manner, but is carried through to the sea. Its accumulation in arid lands, at an appreciable grade, is an effect of imperfect and early arrested drainage. An apron of débris rising high upon either flank, therefore, is characteristic of desert mountains.

A BUILT PRODUCT OF DRY-CLIMATE DRAINAGE.

A mountainous tract in an arid region is, relatively, a humid tract. Its streams may not have the perennial character of streams in a humid climate, but they run strong, and they carry through—i. e., they do not fail appreciably in volume and deposit their load. But beyond the mountain boundaries they deposit, because the climate there is dry. They sustain losses only and are not replenished.

The stream upon the desert proper is dwindled, and finally brought to an end, depositing the whole of the load which it carries in suspension, and a part of that in solution, because of excessive evaporation into the dry air on the one hand, and because, on the other, of absorption into the dry ground. The stream in humid lands runs upon ground already saturated by the local rainfall; it runs also, normally, below the general level, cutting into it and receiving a contribution from the ground water. The desert stream, on the contrary, normally runs and spreads upon the surface, which either it has itself built up or is engaged in building up; and by seepage loss it contributes to the ground water.

All streams are variable in flow, and with respect to their really effective work in erosion, they are periodic. Effective work is done during flood periods only. During the period of light flow, comparatively of long duration, there would be accomplished a considerable measure of work except for the fact that flood flow leaves the stream bed paved with large material, too heavy for the stream in its feeble stages to handle. The stream upon the desert differs from that of humid lands in that commonly its periods of strong flow alternate with periods of no flow at all.

Arid lands are dry not because their atmosphere in equal degree is devoid of moisture, but because the conditions are not favorable for the precipitation of such moisture as it has. Not infrequently, indeed, the heavy rainfall of humid lands is delivered from air which has reached them across an extensive arid tract. The mountainous areas of an arid region are relatively humid areas because they present, locally, conditions favorable for precipitation. In order to pass over them moving air is forced to rise; in rising it is both expanded and

cooled, and expansion and cooling alike diminish its moisture-carrying capacity. Only the nonmountainous expanses of an arid region, then, constitute the desert proper.

The desert proper is without streams, except such as extend into it from locally humid areas—its mountains—and which, after comparatively brief extension, become "lost" upon it by absorption and evaporation. In exceptional cases rivers, such as the Nile or the Colorado, having their rise entirely without its limits, may traverse a desert, and be perennial across it; but the drainage which is normal comes from included elevated tracts, locally humid, is widely variable in volume of flow, and is peculiarly subject to heavy floods.

Streams having this habit of violent flow, following long periods of rest, though they may have brief duration, will yet reach the desert plain heavily loaded; for the processes of rock disintegration will not have been wholly suspended in their headwater region, and the material for loading will be ready at hand. Furthermore, in its upper region of tributary contribution the growing stream will add to its load by erosion of its bed; but upon the dry plain, without tributaries, and rapidly dwindled by absorption and evaporation, it will build, rather, by unloading. Thus, normally, in a dry climate, streams from a mountain range spread aprons of débris against its base, seemingly lifting the range above the general desert level upon a broadly spread pedestal.

Such streams in their mountain headwaters act separately and individually, carving systems of mountain canyons, but upon the plain without, if issuing close together, they may act jointly, extending a uniform slope of mountain waste. The débris apron is the correlative of the fan-form groups of headwater canyons.

This pedestal-building work of mountain streams in an arid region finds its equivalent in humid lands in foothill sculpture. Arid mountains normally are without foothills, at least as erosion effects; and where originally they do occur, in time they become buried in the process of creation of normal foot-slope profiles.

ANALOGY WITH HUMID-CLIMATE CONSTRUCTIONS.

The débris apron is related in manner of construction to the delta of the humid-lands river as well as to the backward-spread bottom land above the delta. It is more nearly of a kind with the plain which, in a climate of perennial drainage, streams in parallel series form along a coast, advancing the coast line, and which in reality is the product of coalescence of individual stream deltas and delta plains.

But these constructions are terminal phenomena of through streams, which extend to base-level at still water and there develop scattering flow, because primarily slope has become almost insensible. They are practically flats at the foot of a long grade. The débris apron, on

the other hand, is a deposit of the intermediate course. The typical arid-lands, or desert, stream does not carry clear through—does not reach to any ultimate base-level. It comes to an end while yet upon a relatively steep grade. For this reason the slope of desert waste material constitutes a topographic feature of appreciable relief and is characteristic and conspicuous in desert scenery as a symmetrically spreading pedestal complementary to the desert range.

A COMPOSITE: THE ALLUVIAL FAN ITS UNIT.

As a topographic individual the débris apron strictly is a composite, just as the coastal plain is a composite. The alluvial cone or alluvial fan, radially spread from the mouth of a canyon, is its unit, as the delta is the unit of the coastal plain. The débris apron is formed by coalescence of alluvial fans in series along a mountain front. The alluvial fan, then, is the desert counterpart of the delta.

FIG. 301.—Tributary and distributary regions of a fan-building stream.

The terminal fan-form construction (tidal interference in the one case aside) is normal to all streams, whether perennial or intermittent. It is a phenomenon of their final and rapid unloading following upon rapid failure of flow, the deposited load in turn reacting upon flow to impede and subdivide it and to deflect it in many divergent courses. In the case of the perennial stream, which goes through to base-level and still water, radial spreading occurs only as a termination to a course of concentrated flow, relatively long. Such a system has its upper region of branching tributaries and its lower region of branching distributaries, with trunk-stream connection, while the stream from the desert range commonly has its tributary region directly united to its distributary region, in hourglass form, at the mouth of a mountain canyon. Alluvial fan building, like delta building, fol-

lows upon failure of flow, but with the difference that in arid lands flow fails, not because grade finally has become lost and flattened out at base-level, but because the stream itself has become enfeebled and finally brought to an end through ground absorption.

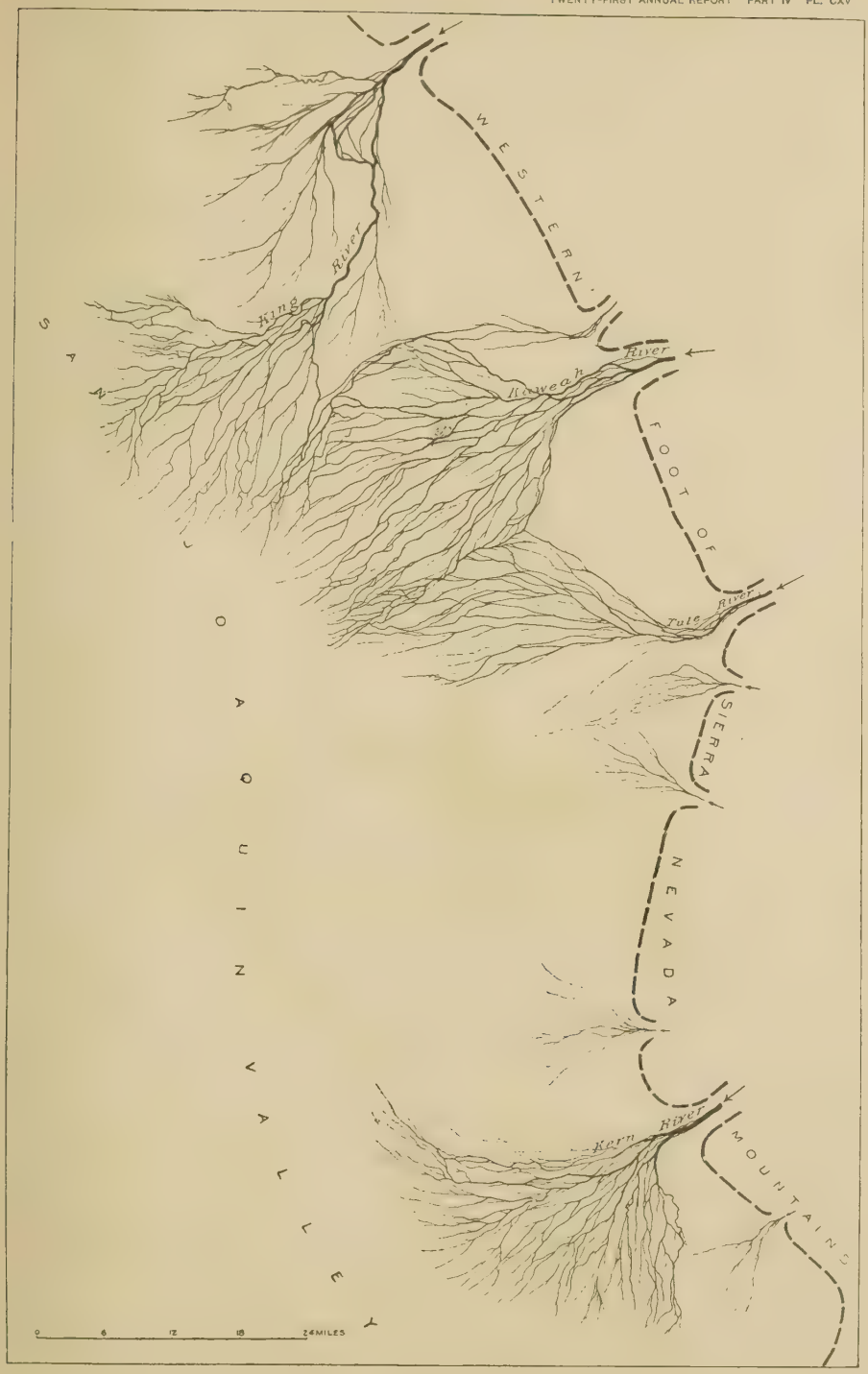
HIGH GRADES THE RESULT PRIMARILY OF STREAM ABSORPTION.

The perennial stream maintains the ground over which it runs in a condition of saturation. In arid lands the ground water of saturation sinks, between the periods of flow of the intermittent stream, and has first to be replenished. The ground water thus robs the desert stream. In transportation of load, stream velocity is the prime factor, but stream volume is a secondary factor and may at times assume primary importance. The delta is built at standing-water level because velocity is brought to an end there on a bed without grade, but on the comparatively steep grade of the desert alluvial fan the load in transportation—relatively heavy because desert degradation is easy—becomes an overload, not because, primarily, velocity is diminished, but because volume is diminished. The intermittent stream finds its end, not at base-level, in the sea, but at an early stage on the way to it in the ground.

As between the desert range and its foot slope, then, the former is the region of relative humidity (because of its relatively high altitude), of stream development through concentrating flow, of degradation, and of loading; the latter, of stream dwindling and failure through ground absorption, of unloading, and of distributed flow. For a given volume of issuing stream the heavier the load the greater will be the tendency to spread, and therefore the steeper the grade, since spreading promotes stream failure by bringing the water into wider contact with the dry and porous ground. Desert streams from unclothed mountain flanks are, as a rule, heavily loaded.

The débris apron will have its own independent precipitation and its drainage of local origin; and this local drainage originating upon it unloaded will tend in turn to degrade it to some lower inclination and to distribute its material farther on. Through recurring local reenforcement of transmission from local precipitation the waste from desert mountains must eventually reach the sea. But in proportion as the run-off from the mountains, reaching out upon the desert, is more vigorous in its scattering transportation and unloading than the drainage of local origin is in picking up again, the waste plain will grow rather than diminish. In short, the slope is maintained at its high grade against a tendency to reduce it, and it must be because it is rapidly built that it has topographic prominence.

This high grade of the apron of deposit is not due, necessarily, to small size of its shaping streams. The streams of humid lands, small and large alike, build flats. Nor is it due to low velocity of flow, for



MAP OF DISTRIBUTARY FANS OF KING, KAWEAH, AND KERN RIVERS, CALIFORNIA.

the stream we are here considering is of mountain origin, and leaves its canyon with a high velocity, which would tend rather to produce a gentle and long grade. It is due to the facts that, being intermittent, the stream issues from its gathering ground overloaded, in the first place; and that, issuing upon porous ground not already saturated, it is rapidly dwindled and made to disappear by ground absorption.

SHEET FLOW AND LACED DRAINAGE.

Since the drainage of a desert range does not flow off from it as a sheet, but rather at points of concentrated discharge spaced along the range front, as a parallel system of streams from canyons, it must thereafter, in order to construct a débris apron, take on something of the nature of sheet flow, by the spreading out of each individual stream, and, at an early stage, by the union of these individual stream fans.

As a matter of observation, actual sheet flow does take place for some distance out from the canyon mouth during periods of maximum discharge. Yet, though the bed of the spreading stream is fairly smooth, there is discernible within the spreading sheet a tendency to flow in currents because the bed is not absolutely smooth. At the same time it will be apparent that the growth of each thread of current, though rapid, is but momentary, and that concentration is here again the next moment followed by spreading, after the manner of the stream as a whole; and as current growth necessarily entails channel cutting, there will take place also increase of the already heavy load, overloading, and deposit.

Against this deposit the channel scar, through backward building, becomes in large part healed. Ahead of it, on the other hand, in consequence of the relief from overload, channel flow is resumed. However, because of the spreading and thinning, it is not resumed as a single channel, but as several minor ones—again after the manner of the stream as a whole. The general tendency would be thus rapidly toward a closer semblance of true sheet flow—that is, toward a closer approach to balance between the opposite tendencies of scour and of building, by rendering oscillations across the mean minute—if it were not that each branching current comes more and more into union with like branchings from currents on either side. In so doing a new, continuing series of threads of swift motion is established—though of somewhat lessened vigor—each approximately central to a preceding pair.

In other words, flow becomes laced. That is, briefly, there is developed within the sheet a net of currents. As no single thread maintains a fixed position, but in the alternation of backward refilling with channel cutting is continually crowded aside, one way and another, the net will be a shifting one, in time working over all parts of the

surface. Thus, because the meshes of the net are flooded across, there may be the semblance of sheet flow for a brief space out from the canyon mouth; but, even within the sheet, effective work will be done by currents interlacing.

Development will not be symmetrical; some threads will gain at the expense of others; but as thinning progresses, this structure, as a persistent one, becomes plainly revealed. The meshes, which are greatly lengthened in the direction of slope, widen at the same time in that direction, with the radial spread of the network, and sheet flow ultimately thins so far as to open to a mere skeleton of lacing currents.

In this open form there is greater extension. Here again, however, inequality of volume among the various threads of current continues and increases, though to the marked advantage of but a few, ground absorption rapidly bringing to an end the enfeebled many, and developing gaps. In consequence, the extreme limit of outward extension is reached by individual streams only, wide apart and still divergent, and commonly with one or more far outrunning the others, until they, too, become absorbed. During the period of full flow the front, thus shredded out, will hold approximately its position, the loose ends, however, not only widely separated, but each shifting laterally, one way and another. At the outer margin of the fan there is rarely to be seen more than a single feeble and failing current, halting and dodging upon its own deposits.

In spite of the fact that the stream early loses the symmetrical fan form of extension, it nevertheless spreads symmetrically its fan of débris, to the farthest reach of its divergent, wandering threads. During any single period of flow of the intermittent stream, these threaded currents wander over a fraction merely of the total surface. They do not distribute uniformly their addition to it. In successive periods, however, successive sets of stream threads wander repeatedly over the whole, and as each patchwork addition is in fact but slight, construction is carried forward with substantial uniformity. In effect, also, considering the successive different courses together, laced flow may be regarded as coextensive with the débris fan.

Recognition of this process of building is important as bearing upon questions of ground structure, in their relation to well making and to the delivery or "flow" of wells. For every stream has a line of swiftest motion, relatively quite narrow, along which its coarsest material is deposited, and broadly bordering which, on either hand, it deposits finer material, so that a débris slope, built up by a virtual net of shifting streams, will have a structure reflecting such a process. It will be a structure, not of bedded sheets, as the alternate occurrence of coarse and fine material in well sections would seem locally to indicate, but of interlaced gravel courses penetrating a mass of fine material.

As a rule, however, it is on a small scale only—by a minor stream from a minor canyon—that the perfect alluvial fan is formed and left isolated. The conditions are exceptional which favor spread to a distance uninterrupted, even upon an unbroken plain. The desert range discharges its drainage from canyons in a spaced series of streams along its front, and commonly, therefore, there is union of the resulting series of débris fans at an early stage in their expansion. Indeed, there is a faint topography in confirmation of what we here theoretically suppose: Close to the range foot the débris slope is undulated along a line parallel thereto; individual fans or cones rise perceptibly to each point of discharge. Somewhat farther out there is undulation, merely broader and fainter; and eventually, so far as the eye can discern, union becomes complete. The streams, in short, build together an inclined plane, rather than each independently an alluvial fan.

Strictly speaking, then, there is no such thing as sheet flow. Where for a space there is semblance of it, the fundamental condition, as shown, is one of intimately lacing threads of current; and while the débris apron itself is in effect a sheet of waste, built up by additions practically sheet form, so that its surface rises uniformly, it is in fact an interwoven mass rather than either a homogeneous or a bedded one.

The degrading stream persists upon a line once taken; but the aggrading stream shifts from course to course, abandoning considerable lengths at a time. And fan building is accomplished not by a net of streams working simultaneously over the whole area, but by a few threads of stream continual shifting, producing a net of stream courses in final plan.

THE GRADED SLOPE.

It is apparent that débris aprons may be accumulations of notable depth. The waste of humid lands goes into the sea and accumulates heavily there only; but arid lands are always deeply cumbered with their own degradation products. The region of through streams has the sea for its base-level of deposit, while the region of incomplete drainage has virtually no base-level at all. Its débris accumulations, however, though in deep masses, are not disordered; they are disposed in graded slopes.

Though the absence of a complete cover of protecting vegetation especially favors degradation, and though (the intervals of quiescence not considered) the wear of desert mountains is in fact rapid, so that they are strikingly pinnacled and sharp, nevertheless, under normal conditions the great body of an arid region will have the appearance of being exempt from even the touch of erosive agency. Its characteristic profiles are long and sweeping; indeed, they are delicately modeled curves.

DEGRADATION AND AGGRADATION.

And yet, in arid as in humid lands the agencies of degradation are everywhere in some degree operative. It is only because in arid lands, on the waste plains, their work normally is feeble in comparison with that of the building agencies that seemingly they are inactive. In humid lands all above base-level is a region of degradation. The effect of drainage in humid lands (conditions remaining stable) is always to take away; never more than lightly and temporarily to add. The waste plains of arid lands, on the other hand, are regions of aggradation. Their mountains are exceptions; it is from the very vigorous wear of these elevated regions that the waste plains are spread, but in arid lands normally—that is, where conditions have long been stable—the mountainous tracts areally will be inconsiderable. The desert range, because high and irregular in outline, where all other lines are symmetrical, is conspicuous; but ordinarily, in cross profile, it is no more than a knob between far sweeping débris slopes. Without mountains, the desert, like the land of perennial drainage, would be everywhere a region of degradation; the rate of degradation merely would be slow.

It should be noted that, while obviously the ultimate effect of the uninterrupted operation of these processes must be reduction of the mountains, complete reduction over large areas is perhaps never attained; for the period required is very long—longer than that of mountain making, and losses are compensated by renewed deformation and uplift.

THE GRADED SLOPE A BALANCED PRODUCT.

Neglecting the slight effect upon waste plains of their local precipitation, the mountain streams which become extended and spread over them tend at the same time both to sculpture their surfaces faintly and to build them up. The long grade is therefore a balanced product. Its symmetrical, faintly curved profile is really an expression of delicate equilibrium attained and established between opposing tendencies—an equilibrium easily disturbed, yet constantly maintained.

This dual process has been termed "gradation." The slope, in profile, will always, with an aggrading stream, be symmetrical—always, indeed, slightly curved; but its average grade, or the average inclination of the curving plain at which its two antagonistic shaping forces are brought into balance, may range from steep and short to gentle and far extended. Thus, essentially, the slope is one of equilibrium. It has been better called a "graded slope." It is, in fact, by cutting and filling, or, in other words, by grading, that the forces which shape it come into equilibrium.

GRADATION A CONTINUING PROCESS.

Strictly, the graded slope, properly to be so called, should be a finished construction. It should be a slope upon which the stream would run without variation either of velocity or of load and without either scouring or building up its bed. By deposit, however, the slope continually grows (up to a certain maximum limit of mountain waste and yield), and at the same time it continually alters its inclination. There is slow departure from equilibrium, and there is closely following readjustment toward recovery of it.

But these modifications and readjustments do not take place at the same rate at all points of the grade. Essentially they are effects of terminal unloading and building propagated backward along the grade, and this propagation proceeds at a slowing rate. In consequence, the profile is curved. With perennial streams—i. e., streams which extend to base-level—this curvature is concave, flattening with terminal building and lengthening. With the periodic desert stream of variable extension, as with the perennial stream, concavity of profile is normal and follows essentially upon terminal unloading. But with the play, or variation in position along the grade, of the stream end such curvature may, in fact, become either accentuated or flattened, or even for a space reversed.

In any event, curvature will be barely perceptible; but that there is curvature at all, however slight, and that it is persistent, shows gradation to be both a process responsive to slight influences and a continuing process.

RELATIVE STABILITY OF GRADED SLOPE.

Under stable conditions—i. e., with unchanging climate and freedom from earth movement—the graded slope passes through these transformations with a slowness comparable to that of mountain wear. Deprived of the greater part of its load, the same stream would at once attack its former slope of equilibrium, and rapidly, though at a progressively slowing rate, lower it. On the other hand, its load largely increased, the stream would rapidly build up the slope. In either case, however, it would come to a stand at a new grade of equilibrium, at some new level, lower or higher, answering to the changed conditions. Contrasted with this promptness of response to abnormal influences, the rate of transformation through which the graded slope itself normally passes is a secular one. It keeps pace with the slow growth of the débris mass following upon mountain lowering, and imposes upon it merely the condition of symmetrical development. That, however, the processes involved in gradation, which raise or lower the stream bed to equilibrium of grade, are themselves essentially rapid is apparent from the swiftness of the alternate cuttings and

refillings, of small amount, in which first one and then the other of the two opposing forces gains or loses the advantage.

As at the surface of a river, the material moves on, while the level of the plain is maintained virtually undisturbed; and, as with the river, if the rate of supply of this material be increased or diminished, the surface of the plain will be correspondingly elevated or depressed—graded up to a higher position or graded down to a lower one. If the disturbance of equilibrium be abrupt, the raising or lowering of the surface to the new position will be accomplished swiftly.

THE GRADATION PLANE.

The term "graded slope" applies to the stream bed in longitudinal profile only. It applies equally to that of the perennial through stream of humid lands, which by channel cutting persists along a definite line, and to that of the intermittent desert stream of shifting habit. But the bed of the humid-lands stream has such insignificant width that it does not in itself constitute an important topographic form. Nevertheless, the entire surface in humid lands, since all of it is drained, may be regarded as made up of an infinite number of drainage courses. The minuter ones are not definitely marked, since with them, as with desert drainage, flow is intermittent, and, when it does occur, amounts to overflow; but the larger ones are fixed in their courses along gullies, ravines, and valleys of their own making. On desert plains, equally, the entire surface is properly to be regarded as a stream-bed surface, but here, over large unit areas, it is virtually the bed of a single stream. The bed of the desert stream, then, is not a graded profile merely, but a plane of gradation, and constitutes a topographic form which is, in fact, the dominant and characteristic feature of desert landscapes.

THE DÉBRIS APRON A PLEXUS OF GRADED STREAM BEDS IDENTICAL IN PROFILE.

In short, not to complicate the statement with details at every point, a series of streams from a mountain range, which in humid lands would persist upon independent courses and excavate valleys, may in arid lands unite by broad branching and interlacing flow and build up the original surface to a smooth and far-extended apron of débris. This débris apron, having the profile of a graded stream bed along all lines in the direction of its slope, will be a gradation plane, sensitive as a whole to any disturbance, by outside influences, of the equilibrium between its opposite grading forces, just as the single profile is sensitive.

DISTURBING INFLUENCES.

While, then, it is understood that the plain of graded stream beds holds a constant level—or a level that, normally, is departed from only by slow, secular growth—it is yet important to recognize that it does so only so long as the conditions upon which its growth has depended remain constant. The gradation level represents merely a balance attained between agencies or groups of agencies, either of which, if this balance were greatly disturbed by outside influences, would swiftly and radically transform the entire surface. It has been intimated that waste-plain development in an arid region has a cycle, the inception of which is mountain birth, through the operation of agencies which need not here be considered, and its close the completion of mountain destruction and leveling, through the operation of the familiar agencies of erosion. At the same time it was pointed out that desert topography bears record, as a rule, of the frequent interruption of these long gradation cycles by earth movement resulting in deformation, with the result always that gradation levels are disturbed and that regradation is set up toward new levels; and in the passage from any such established level, or, strictly speaking, inclined plane of equilibrium, toward a new one, there will be a topography of changing type marking stages in the transition. If, for example, deformation has been of such character that the new plane of equilibrium, or adjustment, is lowered relatively to the old one, the forces of degradation alone will effect the change. The transformation will have two stages, marked by distinctly different topographic types. In the simple and typical case of the mountain range and its débris plain, the streams which formerly upon issuing from the range spread toward one another, and in so doing built the plain, as in effect a single broad stream bed, will now continue across it in fairly direct, individual courses, steadily cutting downward, and creating in time a parallel series of V-form valleys or canyons. This is the first stage. The canyons will widen at top, retaining sharp edges, but at bottom they will continue to have the width only of the stream itself, until in downward cutting, at a slowing rate, the newly imposed level, or gradation plane, is reached. Here deepening will come to an end, as if upon a rock floor, though the material still continue to be the loose material of a débris accumulation. Here will begin the second stage, with appearance of the new gradation plane, by widening of the valleys at bottom as well as at top, and the development of valley "bottoms."

With the maturing of effects under these new conditions a striking contrast is presented from those of the earlier stage. In the first there is a single plain, sharply dissected merely; but in the second there are two plains, the one of widening valley bottoms, the other of isolated, subdivided, and dwindling plateau surfaces. In the widen-

ing of valley bottoms, to the ultimate union of them all in a continuous new plain at the lower level, with complete removal of the interstream plateaus, each stream is none the less occupied in degradation because it has ceased to cut downward. There is return to the earlier habit of wandering, subdivision, and fan-like spreading, but, in proportion as the valley walls interfere with this tendency to spread and extend the new plain, they are cut into horizontally and are undermined, the displaced material being added to the "load" of the stream. Degradation of this type has been well styled "planation."

When deformation is of such character that a surface which had been brought to grade becomes depressed below grade, readjustment will be by building—by development, first, of alluvial cones or fans, and eventually, through the coalescing growth of these, of a new gradation surface at the new and relatively higher level. But readjustment by dissection and planation to a lowered plane of equilibrium produces topographic forms that are very different.

Desert cycles of mountain reduction and plain building have great duration, because stream work in a region of light humidity is discontinuous. Desert streams are vigorous in work, but their periods of activity are relatively brief. The desert is so called because the condition of dry stream courses and of stream inactivity is the normal one. During these long, dry periods, furthermore, the wind, acting upon a ground surface unprotected or but feebly protected by vegetation, produces effects which, on the whole, hamper the systematic work of gradation. Certain characteristics of the structure and texture of desert-plain accumulations, as revealed in canyon sections, seem to point to this agency as at times accomplishing notable results.

Since desert cycles are of long duration, desert surfaces commonly bear record of repeated interference with these cycles. While profiles prevailingly are smooth and sweeping to great distances, yet not infrequently the slopes will be found to be characterized in detail by a topography of readjustment. They will exhibit multitudes of residual fragments marking earlier and abandoned planes of equilibrium, perhaps of several such planes in series, with slight vertical intervals.

It is characteristic of deserts not only that their plains are large, but that their streams are few. As shown, the plains of the desert constitute the desert proper; the mountainous tracts are not only relatively humid, but small in area; and such streams as the plains have, whenever there is flow at all, are mainly traversing streams—the surplus run-off from the mountains. There is a rainfall of some amount upon the desert proper, but the intervals between rains are much longer than in the mountains. Under stable conditions the influence only of the traversing mountain drainage is perceptible upon the débris plain; but if some disturbing influence, such as local uplift, interfere

A. ABRUPT SIDE SLOPE OF VALLEY ABOVE GRADE.

B. GENTLE SIDE SLOPE OF VALLEY AT GRADE

with the spreading and depositing habit of the traversing streams and cause them to erode instead, and to flow in single lines, in valleys, then the interstream areas—upland flats—will be left wholly to the influence of the local precipitation. This local precipitation may or may not develop drainage and accomplish some measure of degradation of its own. The ground is dry and commonly of a more open texture than in humid lands. On the other hand, desert rainfall is usually heavy during its brief period; but because the period is brief there may be complete absorption and no run-off whatever, if there happens to be fairly close-set vegetation to act as a cover.

There are degrees of aridity, and there are corresponding differences in the character of desert vegetation. But there is not a like gradation in the erosive effect of the local precipitation upon desert plateau surfaces. Either they are more or less intricately cut up or they are left virtually in the large, unmodified tables blocked out by the mountain streams. Either there will be a considerable degree of erosion or there will be none at all, according as desert conditions are severe or only semiarid. It follows that semiarid or "subhumid" tracts in arid lands, where they bear record of interruption and reversal of gradation cycles, will have a distinctive topography, commonly in light relief, of broad alluvial plateaus. Obviously these plateaus, thus held above grade against a precipitation greater than that which is sufficient for the intricate sculpturing of more arid tracts, have a precarious hold on existence. Their surfaces are protected because they have slight grade. They could not be thus protected on the sharp slopes of matured drainage lines. Hence, if drainage were to be once initiated, degradation would be swift. "Bad lands," which commonly occur in regions not extremely arid, possibly have origin in such delayed degradation, set up finally by temporary shifting of climate to severely arid conditions, as by a protracted series of droughts, killing vegetation.

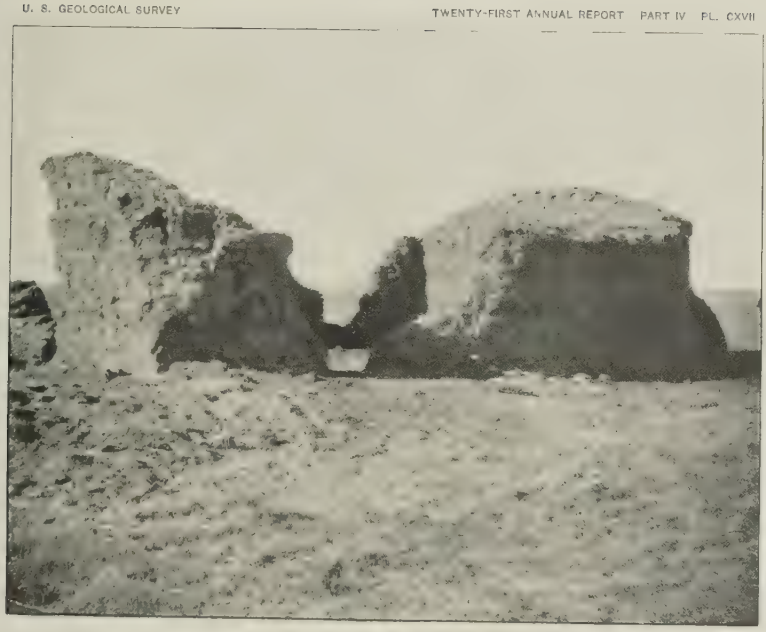
Thus the vegetal cover may be a conserving factor of much importance in arid regions. The most effective covering, outside of regions of tropical vegetation, is sod. On deserts proper, grass, where it grows at all, grows only in tufts. Nor is there continuous sod even in humid lands, where the ground is overshadowed in greater or less degree by larger growths. But in subhumid lands, upon plains, sod is universal. Thus the subhumid belt of the Great Plains—i. e., the High Plains—is referred to in the adjoining arid and humid belts, to the west and the east, respectively, as the "short-grass country." In the appearance of its covering it is in marked contrast with the "bunch-grass country" to the westward. The short-grass country might, in fact, appropriately be termed the "sod belt." This character of a sod belt is strikingly brought out in the contrast presented in the nature of materials used in house building by the pioneer, here and to both the

east and west in the humid and arid belts of the plains, respectively. In the short-grass country the pioneer builds with sod, because there are no trees. In the humid belt he has the choice between sod and logs, and he builds with logs. The humid plains are not timbered, but trees line the streams. They would line streams in the subhumid region also, but that region is virtually without streams. To the westward, in the arid belt, however, there is neither sod nor timber, and there the almost universal building material is, of necessity, "adobe" or sun-dried mud.

There are then, two possible disturbing influences which may result in transformation of the gradation plane—deformation and change of climate. When the disturbance is of such character as to result in degradation, whether by reason of deformation or of climatic change, there are two factors which, on the other hand, make for preservation of the plain, at least against its local precipitation, viz, absorption by the porous and dry ground and evaporation, the vegetal cover, by retarding flow, aiding both. Where the vegetal cover is sod it retards flow completely, not only because the grass blades entangle the water already fallen, until absorption and evaporation can dispose of it, but because blades and roots together resist the impact of rain drops. It is because, in humid lands, the heavy and long-continued rain, by mere repetition of blows, gets at the soil directly, that the rill is established, concentrated flow made possible, and drainage initiated.

THE HIGH PLAINS PLATEAUS REMNANTS OF AN OLD DÉBRIS APRON.

The High Plains in several respects are notable topographic forms. They are gravel plains unscored by drainage, yet standing in relief. The Arid Region affords many examples of gravel-plain plateaus, but on a small scale. These of the Great Plains slope are remarkable by reason of their extraordinary dimensions. The common understanding of a plateau is that, structurally, it is a rock-sheet platform, owing its form and its survival to this horizontal structure and the resistant character of its material. The High Plains, on the contrary, are of soft material, unconsolidated, or but very partially and lightly consolidated. There are such plains, built under water and subsequently uplifted, which have a structure representing the extreme of evenness in the grading of materials. Also there are soft plains of glacial origin, representing in their mass the other extreme of no orderly structure whatever. But the High Plains exhibit, in the main, in their sections, both artificial and natural, unmistakable evidence that they were built upon dry land by streams. They are remnants of an old débris apron. Their surfaces are residual patches of a former vastly extended gradation plane. That this is so—that the deep silt, sand, and gravel accumulation is of fluvial origin—unmistakably appears upon detailed examination of its composition and structure.



A

B

SOD HOUSES OF THE SUBHUMID PLAINS.

SOURCE OF THE MATERIAL.

The gravel is disposed in courses, always, so far as they are traceable, closely following the direction of slope of the Plains. It is far traveled—i. e., is well rounded, and of material which, in long transportation, would most successfully resist both mechanical wear and chemical decomposition. In this respect the gravel of plain-building streams, well away from the source of derivation, differs from shore gravel. The latter, while made up largely of resistant material, well rounded, is nevertheless to some extent graded, including always fragments freshly derived. Again, in the mid-slope region as well as close to the mountains, the Plains gravel is seemingly identical in composition with the harder crystalline rocks of the eastern Rocky Mountain front.[1] It contains pebbles of volcanic rocks eastward of the range foot, in southern Colorado.[2] Pebbles of basalt occur at all levels in canyon sections across the High Plains to the eastward of the basalt areas in northeastern New Mexico. In short, the source of the material was the Rocky Mountains; the agency in its transportation running water—i. e., streams from the mountains—and these, extending into a desert climate, had the desert habit of branching and lacing flow, and built up the desert surface with their burden of débris from the mountains to a delicately adjusted slope of equilibrium.

THE GREAT PLAINS A STRUCTURAL SLOPE SUPERFICIALLY MODIFIED BY STREAMS.

But the Great Plains, as we have seen, are only superficially a débris slope. They are not, for example, like the slope which flanks the Sierra Nevada along its whole western base, forming in breadth most of the Great Valley of California, an accumulation of mountain wash from top to bottom. Except superficially, they are a structural slope of marine-rock sheets uplifted, with generally uniform eastward inclination. They are merely mantled by débris. The traversing streams from the mountains, as the alluvial covering attests, have found the structural surface, however, below "grade," and have at some time brought it up to grade, or have striven to do so, by building upon it. But while the buried rock sheets are virtually uniform in their eastward inclination, wherever the bed-rock surface is exposed by degradation it is apparent that previous to burial they had been eroded. The covered surface had a topography of considerable diversity and relief.

While, then, the Great Plains are to be regarded as in the main a structural slope merely modified by streams, they are yet superfi-

[1] Physical properties of the Tertiary, by Erasmus Haworth: Univ. Geol. Surv. Kansas, Vol. II, 1897, p. 253.

[2] The underground water of the Arkansas Valley in eastern Colorado, by G. K. Gilbert: Seventeenth Ann. Rept. U. S. Geol. Survey, Part II, 1896, p. 576.

cially, and to the depth of their alluvial veneer, a débris apron of the Rocky Mountains. Absolutely, from the point of view of the well maker, the depth of the veneer is often very considerable. It is least close to the mountains,[1] but midway, upon the High Plains flats, it sometimes reaches a thickness above the old valleys of the bed-rock topography of 500 feet.

THREE GRADATION STAGES RECORDED.

In the buried topography of the floor, in the smooth surface of the High Plains, and in the topography of the erosion at present in progress, there are recorded three stages of gradation by the mountain streams—virtually the same streams as at present, since, however devious their courses without the mountains, they must have issued, throughout the entire period, from practically the same series of canyon openings along the mountain front.

Prior, then, to the stage during which these streams covered the Plains heavily with their deposits the slope must have been considerable. The present streams have in places cut through the cover into the old topographic surface, and are there showing a disposition toward planation—i. e., are subdividing in their flow and widening their bottoms. It would seem, therefore, that the eastward inclination during the earlier cutting was probably not materially different from that at present. If it differed at all, probably it was greater, since there is no indication that the earlier streams had anywhere reached down to grade. Hence, to assume that between the early erosion and the present erosion burial of the early surface was accomplished in any other manner than by stream building is to assume a radical deformation in that interval, and yet with a return at its close to substantially the original condition.

But it is not necessary to assume instability of the structural slope. It is not necessary, in order to account for change in behavior of the traversing streams, to appeal to deformation. A sufficient cause may be looked for in change of climate. There is record of erosion, with reversal to deposition and rebuilding, and reversal again finally to erosion, and there is reason for believing that this series of interruptions of the gradation cycle was an effect of climatic oscillation rather than of earth movement.

SURVIVAL WITHIN THE MID-SLOPE BELT A CLIMATIC EFFECT.

As pointed out, the uneroded fragments of the old surface fall within the boundaries of the subhumid belt. Their preservation in this region of considerable precipitation, in contrast with the erosion in both the arid belt to the westward and the humid belt to the eastward, is ascribed to a graduation across the Plains in the character of the

[1] The underground water of the Arkansas Valley in eastern Colorado, by G. K. Gilbert: Seventeenth Ann. Rept. U. S. Geol. Survey, Part II, 1896, p. 576.

vegetation corresponding to the gradual failure of humidity, which in the subhumid belt has developed a universal, close-knit sod. Sod appears to be a most effective covering, while bunch grass, or grass of the same variety or varieties, growing in tufts, affords virtually no protection at all.

Thus the High Plains, of unconsolidated material, above grade, and exposed to a considerable precipitation, are held by their sod. The tufted growths of bunch grass and light "brush" of the arid zone fail almost completely in protection because they do not constitute a continuous cover; and sod, on the other hand, is completely effective, not because it resists the erosive work of well-developed drainage, for that it can not do, but because it prevents the initiation of drainage. It is effective against the first faint beginnings. The great plateau surfaces of the High Plains have to show no systems of drainage, because, presumably, from the commencement of the present erosion stage they have been sod covered, as at present. In other words, the High Plains have endured as alluvial plateaus since Tertiary time, or at least since the opening of the Pleistocene.

While degradation is at a standstill upon the plateau surfaces the topographic belt which they constitute has, however, been appreciably narrowed within the corresponding climatic belt by marginal recession. The limiting bluff, especially that facing eastward, is carried backward by sapping on the part of small streams, or feeble beginnings of streams, originating in springs and "seeps" at the bluff foot. These springs are points of escape, or drainage off, of the upland ground water, which in turn has its origin in the upland precipitation. In this indirect way, by marginal attack, a small percentage of the local precipitation of the plateau areas slowly accomplishes a small degree of degradation. The narrowing of the plateau belt proper within the subhumid belt and the sharp delimitation of the plateau areas along their western edges are due to this action.

But these plateaus, none the less, are essentially ephemeral forms; vegetation is not of sufficiently vigorous growth to hold upon arroyo slopes after the arroyos are once established. As soon as the sod is cut through, the flat plain almost immediately vanishes and a bad-land topography of unclothed dirt slopes is quickly developed. In humid lands vegetation in a measure preserves slopes, in spite of the heavier precipitation, because the vegetation itself is heavier, and a characteristic topography results.

GEOLOGIC DATE OF THE BUILDING.

The date of the building of the great débris sheet, so far as included fossil remains would seem to determine it, might range anywhere from middle Tertiary to early Pleistocene.[1] However, the beginning

[1] Physical properties of the Tertiary, by Erasmus Haworth: Univ. Geol. Surv. Kansas, Vol. II. 1897, p. 280.

of the final and present degradation stage, during which the smoothness of the Great Plains has been in large part destroyed and their surface lowered, with exception of the sod-covered plateaus of the central zone, doubtless dates from the opening of that period of climatic oscillations in the Pleistocene which, in the Great Basin region of Utah and Nevada, gave rise to repeated floodings of large areas and the creation of lakes. Indeed, it is not unlikely that the grading of certain of the minor plateau surfaces of the High Plains, which stand appreciably below the general level, is to be correlated with the several returns in the Great Basin to severe desert conditions during this period, which also are plainly recorded among the old lake evidences.

This alternate flooding and drying out of areas of interior drainage in the Arid Region to the westward is apparently to be regarded as the desert equivalent of the alternate occurrence and fading away of continental glaciation to the northward and of local mountain glaciation in the Sierra Nevada and the Rocky Mountains in even latitudes. In other words, there was in the Arid Region during the Glacial period no accumulation of snow resulting in glaciation except upon a few of the higher mountain summits, but there were large accumulations of water in the western part of that region wherever opportunity for accumulation was afforded. That is, wherever in the Arid Region there was failure of outlet seaward, there was ponding or the development of inland water bodies; not continuously, however, as the record shows, but in a succession of relatively humid epochs.

It does not necessarily follow that these were epochs of increased precipitation. The change may have been one of temperature only, lessening evaporation. Probably in some degree there were both decrease of evaporation and increase of precipitation; but in either case there would be, in effect, a more humid climate, and the streams upon the delicately graded plain eastward of the Rocky Mountains would become correspondingly invigorated. Lessened evaporation alone would result in their invigoration equally with direct increase of volume by increased precipitation, for they would be taken up less rapidly by the porous ground. They would therefore carry their load farther and equilibrium would be disturbed in favor of degradation. They would be affected in the same way by direct increase of volume at their headwaters; that is, by change of climate toward greater humidity the gradation plane would be lowered and degradation of the old plane would result. It is therefore to be inferred that while the interior basins to the westward (in the Great Basin region) were being flooded the sloping plains to the eastward (the Great Plains) were being channeled by streams of increased vigor.

The erosion might, of course, have been brought about by deformation alone, increasing the eastward inclination of the Plains and thereby giving to their streams greater velocity. But not only would

A. EASTWARD-FACING ESCARPMENT OF HIGH PLAINS

B COARSE GRAVEL AT FOOT OF ESCARPMENT.

the explanation by climatic change be adequate; the Pleistocene lakes of the Great Basin afford evidence that such climatic change or changes actually took place. Furthermore, from this same lake record the inference is strong that there was freedom from earth movement meantime. For example, these inland water bodies (several of them approaching in dimensions those of the Great Lakes) as a rule did not overflow their basins, from which it appears that no actual reversal of climate occurred, but only a mitigation of desert conditions. Failing of outlet, they fluctuated in level, with numerous pauses, responsive to the fluctuating climate. As a rule these pauses, corresponding to intervals of climatic stability, were brief, but at certain levels they had great duration, as evidenced by a notable shore topography of embankments and cliffs remaining to the present day. And yet nowhere in this system of far-reaching shore lines, covering in their time record probably the whole of the Pleistocene, is there material departure from parallelism, indicating earth movement.

The destruction of the old surface, of which the High Plains are a belt of great fragmentary survivals merely, began, then, with the opening of the Pleistocene. That the spreading of the mass occurred at an earlier period than this appears from the abundance of included Tertiary fossils. The fact that there are Pleistocene fossils also is intelligible on the assumption that during the return to arid conditions in the Pleistocene, evidenced by the drying away of lakes in the Great Basin, and probably corresponding to the "interglacial epochs," there was resumption of stream building and refilling of valleys. It is improbable, however, that all of the damage was ever wholly repaired.

Hence, with a few small exceptions at slightly lower levels, the High Plains are Tertiary in the date of their building. They were blocked out in plateau fragments in the Pleistocene; but it would seem there can be little question that their alluvial surfaces are survivals, without sensible change, from as long ago as the beginning of the Pleistocene.

To summarize, then, the Pleistocene is defined as beginning with the first continental ice invasion. Here certainly was marked climatic change. The Great Basin ranges, the Sierra Nevada, and the Rocky Mountains responded to it. They bear record of oscillating glaciation. The basin deserts are marked with the shore lines of lakes of fluctuating level, and here and there the record by glacial moraines is interwoven with that by lake shores. In other words, there was increased stream flow from the glaciated mountains draining into the basin deserts. At the same time there must have been increased stream flow from the glaciated mountains draining across the eastern plain. This plain shows evidence of extensive stream dissection of an originally smooth surface; and as it can hardly be doubted that mountain glaciation throughout the Arid Region was synchronous with the general

glaciation of the northeastern humid region, it follows that the beginning of the Pleistocene found the Great Plains slope a smooth surface of soft material.

STREAM DEPOSITS *v.* STILL-WATER DEPOSITS.

This mantle upon the eroded marine-rock sheets is sometimes referred to as the Plains Tertiaries; sometimes, also, as the Tertiary "gravels." In the former of these two designations there is implied subdivision into subformations, or successive widely extended individual beds. Origin by deposit in still water is assumed. But there are no such beds—at least of original structure. There is suggestion of them in the so-called "mortar beds;" but, as will be shown later, these mark cementation levels merely, recording fluctuations of the ground-water plane corresponding to pauses and reversals during the general degradation. In the latter designation—of "gravels" for the mass as a whole—there is recognition merely, on the part of those who have observed the fact, that there is mingled with the heavy accumulations of silt and sand a notable quantity of coarse material.

Until quite recently, however, there has been no serious consideration of the possibility that the Tertiary mantle might have had origin in stream building. There has been no attempt to account for the presence of large gravel in wide distribution. The whole accumulation has been regarded as made up of lake deposits. It is in the main, to be sure, of fine material, as indeed any far-spread fluviatile accumulation necessarily is; but it has been wrongly assumed to have the regular bedding of lake deposits—even of lakes of shifting shore lines; and until recently there has been no recognition, except so far as implied in the term "gravels" applied to the whole mass, that the occurrence everywhere in some degree of coarse material at least renders the general explanation of origin by deposit, in still water, complex and difficult.

The latest statements of the lake-deposit explanation, in which that view was presented without qualification, appeared in 1895. In a paper on Semi-Arid Kansas,[1] Professor Williston describes, first, an uplift, followed by erosion, during which the floor topography was given shape; second, a reverse movement, resulting in "a series of extensive fresh water lakes extending from Dakota to Texas," in which deposits of débris from the Rocky Mountains were laid down; and, finally, uplift again, with erosion of the lake floors, "leaving on the uplands an immense area of remarkably flat lands with a gentle inclination toward the east." And Professor Hay, in a discussion of the water resources of northwestern Kansas and adjacent territory,[2] indicates a belief not only that the deeper accumulations, well out from the moun-

[1] Univ. Kansas Quart., Vol. III, No. 4, 1895, pp. 213–214.
[2] Sixteenth Ann. Rept. U. S. Geol. Survey, Part II, 1895, p. 569.

tains, are lacustrine, but refers to indications even "that the Tertiary lakes extended into the mountain valleys."

As already pointed out, the trend of the buried ridges and valleys is fairly in accord with the run of the present streams. Hence, on the assumption that burial was accomplished in standing water, there must have been either regional subsidence to a general level or repeated and shifting local deformation; and, whatever the nature of this disturbance of grade from an inclination giving something like 1,000 feet of rise in 100 miles down to a level condition, there must have been recovery from it at the close to virtually the original grade, as seen in the Plains at present. In short, the vertical movements appealed to must have been of vast magnitude, and widely extended.

The evidences directly exclude marine origin; they only indirectly indicate origin in lakes, and they do not exclude stream building. It is because such deep accumulations, far distant from any field of erosion, have heretofore been taken as necessarily indicating still-water deposit, that they were assumed to be lacustrine. They could not be marine, since the included fossil remains are of land animals.

Determination of the question should be possible from detailed examination of the structure of the mass, especially of the distribution and arrangement of its coarse material. The importance of the existence of gravel—even the fact of its existence—at all levels has not been generally recognized.

WIDE DISTRIBUTION OF THE GRAVEL.

Where there is no erosion of the surface there is no gravel at the surface. The eroded areas of the Plains Tertiary here and there show superficial gravel; the High Plains surfaces do not. They have a hard "adobe" soil—except where, over comparatively small areas widely separated, it is covered by drifting sand. But well sections, canyon sections, and the shallow beginnings of erosion at the plateau edges occasionally show gravel close to the surface. All sections, artificial and natural, whether near to the mountains or far out, show a no less frequent occurrence of it at one level than another. Nor is there observable any graded variation in the size of the gravel, up or down, in section. There is gradual diminution in size from the mountains outward, but the rate of this diminution seems to be the same at all levels.

SIZE OF GRAVEL IN THE HIGH PLAINS BELT.

The maximum size of gravel in the High Plains belt is that of cobbles. Material so coarse as this is quite uncommon; yet from northern Kansas to the southern limits of the Staked Plains of Texas the writer has occasionally found beds of cobbles, and no more frequently at one level than another, though seldom, as we have seen, any coarse

material actually at the surface, upon the uneroded uplands. Individuals of larger size—bowlders—are here and there to be found. As a rule these are not thoroughly rounded; they are of the nature of erratics, and probably have been transported either by river ice or in uprooted trees, and they may be of the softer rocks, such as sandstone, while invariably the gravel in beds is hard.

But though bowlders and beds of cobbles are rare, in sections of the High Plains, smaller material, which would still be regarded as coarse gravel, is comparatively abundant.

THE GRAVEL COURSES.

At several localities within the High Plains belt, where natural sections are afforded, the writer has been able fairly well to determine the outlines of gravel beds, and invariably these have been found to be greatly elongated in the direction of the slope of the Plains, or approximately in that direction. Also, they are prevailingly cross bedded. In short, they plainly mark the channel courses of eastward-flowing streams. The valley or broad canyon of the Canadian—a mountain stream limiting the Staked Plains on the north—has several short tributary canyons, affording north-south sections. In the walls of these tributary canyons it is apparent that the beds are cut across, while along the side walls of the main valley they are exposed longitudinally, for in the latter case they are relatively very long.

Immediately to the eastward of the High Plains, in the eroded area of the Tertiary, such exposures often are numerous. The gravel courses can then be made out somewhat definitely. In some instances they are thus closely traceable, with their branchings, for several miles. Where the erosion is not of the bad-lands type—that is, where divides are broad and slopes gentle—differential washing will sometimes result in a superficial accumulation of gravel, so that wagon wheels grind upon it as though running upon macadamized roads. These superficial gravel areas also are spaced apart, in north-south order, as belts extending eastward; and they will each be found to cover, not a continuous bed of gravel of equal breadth, but a net of gravel courses, with the meshes drawn out long in east-west direction. Pl. CXVIII, *B*, illustrates the character of the ground surface over a belt several miles in width, beginning at the foot of the uplands at the head of Pease River, Texas, and extending eastward fully a dozen miles. In the much broader areas of fine material, between the belts of surface gravel, well sections and canyon sections often here and there develop gravel beds again at various depths.

SAND BEDS AND "CLAY."

Of the sand, as of the gravel, it may be said that it is disposed in beds with eastward elongation, only the sand beds are deeper and broader. The gravel courses are interwoven through them.

A. SURFACE GRAVEL IN ARROYO ON STAKED PLAINS

B. [illegible] GRAVEL IN WATER BE[illegible]

Yet gravel and sand together constitute much the smaller part of the total bulk of the Tertiary accumulation. Very fine material (the barren "clay" of the well maker) constitutes the body of the mass, through which the coarser materials are extended in layers at varying intervals and of varying thickness. The well maker should understand this complex structure, and should recognize that, while the occasionally embedded masses of coarse material, from which alone water is obtainable in appreciable quantity, are not continuous geological "formations," they are nevertheless not mere "pockets," but have extension in a constant direction and often may be easily followed with lines of wells.

LARGE GRAVEL NEAR SURFACE NOT OPPOSED TO HYPOTHESIS OF STREAM BUILDING.

It might at first sight appear that in the building up of a plain to a graded slope of stream equilibrium throughout there would be gradual diminution in the velocity of stream flow as the rate of building lessened and the slope of equilibrium was approached, because grade would be gradually lessened also. But grade would be lessened only in a narrow zone at the beginning of the slope; over the remainder it would be increased.

Every stream has its upper region of erosion and its lower region of building. In longitudinal profile normally it is concave, concavity

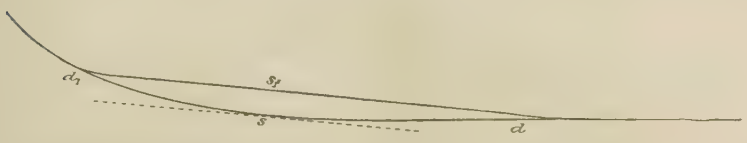


FIG. 302.—Flattened grade profile of stream, after change from degradation to aggradation.

being pronounced toward the head and slight toward the foot; that is, there is flattening in the region of unloading. Hence, if, without earth movement lessening declivity, but as a climatic effect solely, a stream have its point of change from degradation to building shifted backward, the portion of the profile thus affected will have its concavity flattened by filling in, as in fig. 302. Yet, though flattened—i. e., changed from a hollowed profile to a straight one—the new profile, through the greater portion of its length, will have a steeper inclination than the old one had. If, for example, in the figure, the point where deposit begins (or where ultimately it will begin under completely readjusted conditions) be shifted back from d to d_1, the new slope will have less inclination than the old one down to a point s_1; but below that point it will have greater inclination. Also, the new perfected slope will not be reached by accumulations beginning at d_1 and gradually extending outward, with diminishing grade, as in fig. 303, but

by accumulations beginning at d and gradually extending backward with increasing grade to d_1, as in fig. 304. A graded slope is finally reached and building comes to an end, not because the stream has failed in transporting power and runs clear, but because with declivity and velocity of flow increased to a point where the constant supply of mountain débris ceases to be an overload, it no longer deposits, or at least it alternately deposits and picks up again equal amounts.

As already shown, cessation of work is not absolute. The apparent stability is relative only. There is lengthening at the foot, and slow backward building; and there is slow lowering at the upper end in the

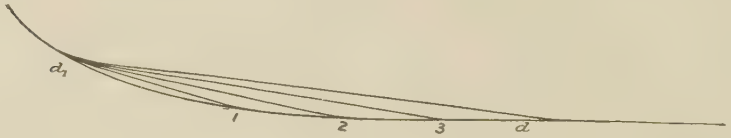


FIG. 303.—Successive grade profiles in the building of an aggradation plane. An incorrect representation.

region of erosion. But in the middle course, along the slope in the main, and, of the Great Plains slope, that portion in which the plateau fragments of its old surface are situated, there is attained virtual stability of position in comparison with the previous rapidity of building from the abandoned grade of equilibrium up to the new one.

Thus building results from stream feebleness, or from imperfect transportation of load; and it ceases when, with continual increase of declivity, the stream finally has become equal to full transportation. Hence, at any given distance out upon the rising plain, there will not necessarily be, as might at first sight appear, gradual decrease in the

FIG. 304.—Successive grade profiles in the building of an aggradation plane. A correct representation.

size of material carried and deposited. It would seem rather that there should be increase, and that the last addition to an aggradation plain would exhibit the coarsest material. There is another factor to be taken account of here, however. With the rise of the surface, and its increasing inclination at the same time, as shown in fig. 304, there is retreat upstream of the point at which subdivision of flow begins, so that while velocity of flow is increased, volume of flow, with each individual channel, is notably diminished. This is a quantitative factor and can not be evaluated. Until it became extreme the effect of shallowing would be slight, while the effect of increase of

velocity would at once be marked. At least it is not against the hypothesis of origin by stream building that the mass shows equally coarse material at all levels.

INCREASE DOWNWARD IN THE SIZE OF BEDS OF COARSE MATERIAL.

It is generally held by well makers that the heaviest beds of coarse material lie near the bottom. This is the view also of Professor Hay, only he goes so far as to divide the mass into two distinct formations—a lower one, the "Tertiary grit," made up largely of coarse material, and an upper one, the "Plains marl," containing no coarse material.[1] He says of the thickness of the marl that it "varies from a few feet to 200," leaving to the grit a much greater average thickness, and sometimes the thickness nearly of the whole.

To the southward, in the High Plains belt, as a rule there is deeper erosion on the part of the eastward-flowing streams than to the northward. The Cimarron, the Beaver, and the Canadian rivers, as well as several lesser streams to the eastward, which have extended canyons into the Staked Plains by headwater recession, have cut through the Tertiary into the floor for greater or less distances—the Canadian across the full width of the belt—exposing complete sections. There are also a few exposures of like character in northwestern Kansas. From examination of these sections, here and there where they are clearly displayed, it appears to be a fact, as the well makers maintain, that there is increase in the size of beds downward. While the beds do not carry larger material at the lower levels, they are thicker and broader there and are more easily traceable. At the same time, however, they are farther apart. It does not appear, therefore, that there is appreciable difference in the total quantity of gravel from level to level; the net of interlacing courses merely is finer and closer above, heavier and more open below. If there is, in fact, as extended field observation seems to indicate, any general law of thickening of beds downward, there are occasional important exceptions to it. At horizontally wide intervals thick beds occur in the upper levels.

Decrease in the size of channel courses, in rising order, together with increase in their number, as with these gravel beds, should follow in the building of an aggradation plain as a consequence of the progressive shifting backward of the point at which stream subdivision begins. But not only is the dry-climate stream periodic in flow, it varies greatly in volume as well, and, like all streams, at long intervals it is subject to exceptional floods. In the case of a plain of rising grade, the effect of the exceptional flood will be correspondingly to advance again the point at which subdivision begins, and to erode for itself upon the plain a broad and shallow trench. That is, there will

[1] Sixteenth Ann. Rept. U. S. Geol. Survey, Part II, 1895, pp. 569–570.

be concentration and trunk flow for the moment, but concentration will be imposed upon the normal flow for a time thereafter, until the trench is refilled. Thus, also, the occasional east-west belts of relatively heavy interlaced beds, above referred to as occurring in the upper levels, exposed by erosion, are explainable on the hypothesis of origin of the whole accumulation by progressive stream building. Furthermore, they at least are stream courses unmistakably. Therefore the supposition of lacustrine origin for the bulk of fine material which they penetrate becomes a violent one, since it is necessary to assume repeated deformations, back and forth, from a horizontal position of the plain, affording opportunity for the thick silt accumulations, to a sloping one affording opportunity for stream work

STRUCTURE IN THE FINER MATERIALS.

But the bulk of fine material which the gravel courses penetrate is not wholly structureless. The gravel courses illustrate, in a conspicuous way, a type of structure which is often to be detected in the heavier sand beds also, and which seems to be characteristic especially of the innumerable minor streaks of sand.

Well makers insist on the frequent occurrence, within the limits of the High Plains belt, of deep and widely extended masses of clay. These are to them barren grounds. Under the general term "clay," however, they include indifferently all fine material, even clean sand, if very fine and interbedded thinly; and this fine sand, where the clay masses are exposed in section, will commonly be found to be disposed, not in broadly spread sheets, but in innumerable disconnected streaks, long also in direction of the general slope, like the gravel courses. No account is taken of these, since their water-bearing capacity is insignificant. They carry (below the water plane) unimportant "veins" of water only. With the first settlement of a neighborhood, and the beginning of well sinking, it will sometimes happen that there will be outlined an extensive barren tract, or clay mass. As within its limits the number of wells increases, however, and especially as the depth of sinking increases, as a rule gravel will be encountered here and there at varying depths. Nevertheless, broad and thick sheets of clay do occur, and such accumulations must be deposits from virtually quiet water.

An elongated clay mass is described by Prof. Erasmus Haworth as occurring near Garden, Kansas, close to the surface, and extended in an east-west direction.[1]

Such an oblong lenticular mass lies to the north of Garden, along the north part of the Arkansas River Valley. Here, for a distance of 4 to 6 miles along the river, is a narrow strip lying just back of the river valley proper, beneath which the clay

[1] Univ. Geol. Surv. Kansas, Vol. II, 1897, p. 274.

exists from 75 to 100 feet in thickness. Many attempts have been made to obtain water in this particular area by different citizens, each of whom has usually abandoned his well because it was known that only a short distance either north or south water could be found in the sand beds at comparatively shallow depths, while if drilling was continued in the clay area a depth of 100 feet or more would have to be passed before water could be reached. The clay beds by no means are confined to such lenticular masses, but frequently appear as thin masses of clay spread out between layers of sand or gravel.

The writer made especially careful examination of this particular clay mass, by means of trial well borings, to determine its dimensions. While from the well maker's point of view there is barren ground of about the area and depth given by Professor Haworth, it is made up of a closely assembled group of elongated clay beds separated by thin sand beds and occasionally by fine gravel. In a single instance only was pure clay for any great depth encountered, and this depth was 46 feet. At many points upon the High Plains, however, deep borings have encountered clay through the full thickness of the Tertiary, interrupted at wide intervals only by thin sheets of sand. Often in such cases other wells in east-west order for several miles will get much the same disappointing results for considerable depths, while, on the other hand, at relatively short distances in north-south order gravel in thick beds may be found both near the surface and alternating rapidly with sand and clay to the bottom.

The clay bodies, especially considering their lenticular, east-west form and arrangement, are not opposed to the hypothesis of stream origin for the entire mass. Fluvial building, as may be observed in the case of all great rivers which have extensive flood plains—notably, for example, in arid lands, the Colorado below the junction of the Gila—proceeds over broad areas mainly by silt deposit, with sand in diverging and subdividing bands, while gravel is to be discovered only in freshly uncovered channels or occasionally interbedded in their banks.

In short, the Tertiary mantle of the Great Plains slope has the character of river deposits everywhere—i. e., in the main, a mass of silt, penetrated with sand and gravel in linear arrangement, but in lines slightly divergent and crossing—and the coarse material is of so frequent occurrence that the whole loose accumulation is sometimes referred to as the Tertiary "gravels."

CEMENTATION.

The mantle is not absolutely loose and unconsolidated. As a whole it is feebly cemented, mainly with carbonate of lime. The cementation is slight, however, not because lime in this form is present only in small quantity—it is, in fact, abundant—but because, as a rule, it binds feebly.

Of the nature and occurrence of this cement Professor Haworth says, speaking of the Tertiary in Kansas:[1]

> The cementing material of nearly all the Tertiary sands and gravels * * * is calcium carbonate. A few exceptions are known to this rule. There is a sandstone near Long Island, in Phillips County, which is so firmly cemented with silica that a rock similar to quartzite has been produced. On the uplands north of Stockton likewise a silicious cement has been deposited between the grains of sand, producing a rock which is quite like quartzite. Near the Saint Jacob's well, in western Clark County, silicious cement has been deposited between the grains of sand, forming a close-grained rock. But throughout the Tertiary area of the State, with these few exceptions, wherever the sand and gravel are held together by any kind of cement it seems to be calcium carbonate. * * * The degree to which this cementation is carried is astonishingly great.

Carbonate of lime, visibly present, is an almost invariable characteristic of the desert plain—a sign of aridity. All streams carry rock materials in solution, as well as a visible load in suspension; and commonly they are more or less "hard" with dissolved calcium carbonate. But only desert streams deposit this chalky material upon their waste plains in appreciable quantity. The desert stream, not running upon ground already saturated, like the stream of humid lands, is in consequence, as we have seen, dwindled in large part by ground absorption; but nearly complete evaporation will occur where, by thin flooding over earlier broad silt deposits and by flood subsidence, it is left in slack-water sheets. Issuing from its headwater region sensibly fresh, the desert stream in time, upon its waste plain, by evaporation and concentration, becomes barely drinkable. Its final disappearance is characteristically marked by the appearance of a white incrustation; and immediately following complete desiccation there will be arrest and return, by capillarity, of some portion of the downward-soaking water, with addition of its solution load to the surface deposit and to a shallow subsurface deposit.

The intermittent, shifting stream, at a later period running in full volume where before it had run but feebly, will tend by re-solution to pick up this incrustation and carry it forward to more porous ground, where, by deep penetration, it will be contributed to the impurities of the ground water. But the calcium carbonate—making up originally a small part only of the load in solution—will resist re-solution. The chemistry of desert deposits has not been fully worked out. Lime carbonate is insoluble in pure water, but is dissolved by the addition of carbonic acid. This, in small degree, rain collects from the atmosphere. Lime is widely diffused in nature, and presumably, therefore, streams, which have their ultimate source in rain, quickly load themselves to their full capacity, as measured by the carbonic acid present. Hence desert streams reach the waste plain charged with carbonate of lime to their full capacity. Of this chalky material, they can not pick

[1] Univ. Geol. Surv. Kansas, Vol. II, 1897, pp. 267–268.

up, in solution, what had been evaporated out from the scattered fringe of previous flows. That which already had been deposited will remain so far at least as stream action is concerned and by repetition of the process there will be accumulation.

But the water of local rainfall may pick it up, and in powdery form its solution will be easy. In so far as local rain reaches to the ground water, some lime carbonate will be carried there. The remainder will be deposited, as before, both at the surface and at a slight depth beneath. Beneath the surface, however, there is everywhere observable a marked tendency to take on the character of root-form concre-

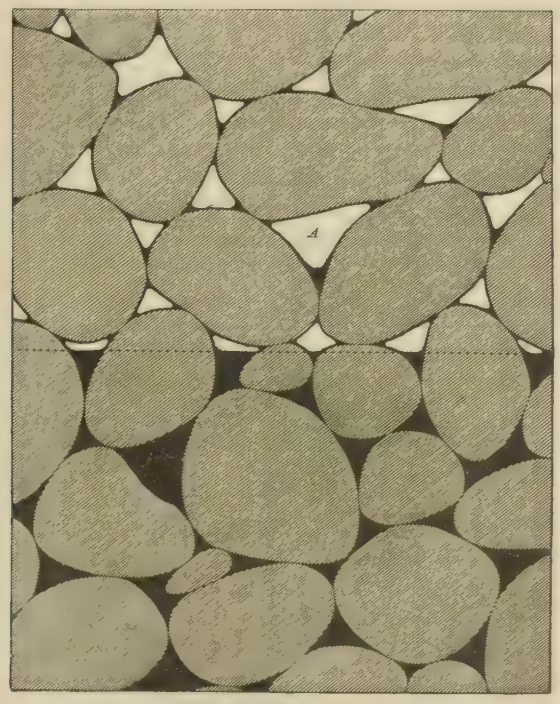


FIG. 305.—Capillary water.

tions, and in this hard form rain water in its brief downward passage will have greatly lessened effect upon it.

Thus it would seem that, in the upward building of an aggradation plain in an arid climate, the building of lime into the mass must necessarily follow as a consequence of aridity. And cementation, in some degree, should follow as well. By interference and union of the lime concretions the ground will be knit together. Frequently, in fact, such knitting is conspicuous.

Furthermore, to some extent individual grains of the groundmass

should become coated, and at their points of contact stuck together, as an effect of deep drying. Everywhere, as a rule, there is feeble binding of this character. Deep drying and slight cementation should result as follows:

The ground is merely moistened, as water soaks downward, until some impervious stratum or floor is reached; thereafter, by accumulation, it becomes saturated; i. e., the openings between its grains become completely filled, as shown in solid black in fig. 305. The upper level of saturation by accumulation is the water plane; but even below the influence of capillarity not all of the downward-soaking water will reach the ground-water accumulation. All the way to the water plane a portion will remain behind to wet the grains of the porous ground and partially fill the voids, as at *A* in the figure. That is, every grain of sand, silt, or gravel will detain and hold a film coating of water by adhesion until the interstitial air has taken it up by evaporation. For example, if a box with perforated bottom and deeper than the lifting reach of capillarity be filled with sand, and water in considerable quantity then be added, not all of the water will in time escape at the bottom. Some portion will be removed by evaporation. After dripping has ceased the sand will still remain wet, and will continue wet until dried by evaporation.

In nature this process must result in surface deposition, around grains, of the mineral matter previously in solution in the coating film of water. As upon a larger scale at the surface, partial re-solution, leaving lime only, will follow with the passage downward of an excess of water after subsequent stream runs and after rains. By repetition and the continual separation out of lime carbonate, grains will come to have an appreciable coating of that mineral, and at their points of contact their coatings will be continuous one with another; in other words, there will be cemented union. An ultimate effect would be the filling of interspaces as well—i. e., complete consolidation of the mass.

But as yet, in the Plains Tertiary, consolidation has progressed only so far as to be just appreciable in the mass, as a whole. It is appreciable to the well maker, in that it is not necessary, as a rule, in dry ground, to wall up dug wells, even where, as sometimes happens, the water plane lies at a depth of so much as a hundred feet. Nevertheless, by contrast with the marine rocks beneath, the Tertiary is a relatively porous and loose accumulation upon a hard-rock floor.

Thus the sloping desert plain in a measure performs the same office toward the streams which scatter over it, and in part are dried upon it, as the desert lake without outlet performs toward its entering drainage. The latter receives from its tributary streams, and retains, their very light burden of dissolved mineral matter; and in time, with removal by evaporation of water in amount equal to the inflow, leaving that matter behind, it becomes heavily charged. In like manner the débris

slope separates out and accumulates carbonate of lime. By continual deposit upon the surface during growth of the mass, and by continual redistribution downward, the whole mass in time becomes impregnated and its grains stuck together.

It should not be overlooked that some proportion, large or small, of the free lime which is so characteristic of the desert plain doubtless originates in place, by decomposition of the already finely subdivided groundmass, just as, in the headwater region of the streams, there is decomposition of rock materials after their mechanical disintegration by frost action and by sharp variations of sun heat. The agent, in the one case as in the other, would be the local rainfall, carrying solvent carbonic acid. We have to consider here a rainfall relatively very feeble; from it almost wholly the ground water is accumulated, because drainage away of the ground water is exceedingly slow; but often it will fall too feebly, or upon ground too difficult of penetration, to escape complete evaporation before it reaches the plane of saturation. Along the temporary course of a shifting, intermittent stream the local rain, as already pointed out, will find stream-deposited lime ready at hand; but after the stream has for a time taken another course this deposit will become washed out, and subsequent rains will occupy themselves in decomposition to an appreciable extent of the ground materials, so far as they may prove to be readily soluble.

To this local decomposition Professor Haworth is disposed to ascribe in notable degree the occurrence of free lime in desert accumulations.[1] Doubtless there is much chemically decomposable matter in the silt of a débris slope, but the larger particles, including the finer sand, of which there is a large body, is mainly siliceous and insoluble.

THE "MORTAR BEDS."

To the rule of feeble consolidation of the mass as a whole, however, there are striking exceptions. Standing out as horizontal ledges on valley slopes, with the comparatively loose material both above and below, and to be encountered also in well sinking, are sheets of comparatively hard rock. In composition and structure, except as regards the presence of cementing material, they in no way differ from the rest of the mass. They are of silt, sand, and gravel, and their cement is carbonate of lime. They are, in fact, sheets of sandstone. But their included lime is so conspicuous a feature that they have been termed by Professor Hay "mortar beds."

The mortar beds are to be met with in well boring at all depths. Though horizontal, or having the inclination merely of the general slope, they are rarely to be encountered over any considerable area at equal depths or in equal number. That is, they are not widely

[1] Univ. Geol. Surv. Kansas, Vol. II, 1897, p. 270.

extended "formations." Furthermore, their coarse sands and their gravel commonly show strongly defined cross bedding; and sometimes, in natural section exposures, this cross bedding will be found to be continuous through them, out of soft material above, into soft material again below. In other words, they are not lake beds, nor even beds of original structure, but cementation levels. Apparently they mark fluctuations of the ground-water plane.

During the third stage—the present erosion stage—of stream work upon the Great Plains erosion has not been uninterrupted. There have been pauses, and, in some degree, returns to building, with refilling of valleys. The ground water is only relatively motionless; it has slow seepage movement; but given a graded condition—i. e., adjusted as to slope—of the débris mass through which it is extended, its upper surface will stand motionless, or virtually so, having slight seasonal fluctuation only, because its loss by seepage is compensated by periodic additions from the local precipitation. The position in depth of the ground-water level (strictly a slope), like the level of a lake without outlet, is determined by adjustment between loss and supply.

Given, then, stability of climate, with graded stability of the ground surface, the water plane will hold a slightly oscillating position at a depth representing balance attained and maintained between drainage off of the ground water and annual replenishment of it from above. Hence, change of climate toward greater humidity, resulting in progressive dissection of the sloping plain by its traversing drainage, will result also in corresponding lowering of the ground-water level; just as artificially, on a small scale, the ground water is lowered by ditching in marshy ground. But a pause in this process would bring the water plane again to a stand; and reversal, with valley refilling, would raise it.

The old lake evidences of the Great Basin bear record, not only of long progress toward more humid conditions, but of many pauses, long and short, during that change, and of many temporary reversals. And apparently the gently inclined cementation sheets of the Great Plains slope are the corresponding record of like changes there. It is at least clear that they mark cementation planes merely, and are not beds of original structure, since their upper surfaces show straight lines intersecting structure.

But while it thus appears that the process of consolidation has in the main been sharply localized along occasional horizontal planes within the mass, and while also it is hardly to be questioned that the water plane, for considerable periods at a time, has stood virtually motionless at various definite levels, so that a causal relation between a succession of water levels and the succession of cementation levels is reasonably to be inferred, nevertheless the explanation of the maximum

A

B

MORTAR-BED TOPOGRAPHY AT MARGIN OF HIGH PLAINS.

consolidation along a water level is not apparent. The mortar beds are not merely zones in which the contained lime, common to the mass as a whole, has taken on the character of cement more completely; lime is present in greater quantity as well. It does not appear that they received this excess by downward concentration out of the loose material immediately above, for there is no noticeable freedom from lime there. That there is in fact excess, however, is apparent from the abundant development of concretions, clearly to be noted wherever the mortar beds have extension through fine material. In such cases weathered exposures commonly show a knitted concretionary structure, lines of cross bedding, entering from the loose material, becoming confused and barely traceable. The process of consolidation here appears to be the same as elsewhere in the mass, only carried to an extreme.

There is progressive increase from north to south in the High Plains belt in the degree of cementation, and as cementation in general increases the mortar beds become more numerous. In northern Kansas they are encountered by the well maker as occasional thin sheets only; at the southern Kansas border they are distinctly more numerous and thicker, while in the Texas Panhandle they make up the greater part of the exposures in canyon sections. The erosion topography of the Tertiary gives expression to this change by increasingly sharp development of mesa forms southward. Apparently, also, individual beds become heavier. Since, however, these thick beds exhibit a pronounced horizontal stratification, with marked alternations of relatively hard and soft layers, it is probable that they represent merely a close crowding together in vertical order of many beds. This close grouping will sometimes attain a thickness of 50 feet. Where their lines are well defined their strict horizontality is marked also, but single lines very rarely have uninterrupted extension for so much as a mile. The grouping only, with vertical thinning or thickening, may continue far.

In apparent explanation of this interrupted extension along a single horizon it may be said that strong consolidation is rarely to be observed in the finer materials. Mortar beds are made up mainly of cemented coarse sand or gravel. Recurring to the assumption that they have origin in concentrated deposit at the water plane, the suggested explanation may be extended in this manner: The deposit is made from downward-soaking water, not from the ground water itself. It occurs in largest amount where the largest contribution from above is made, and a relatively small contribution will be made where the ground is relatively impervious.

It remains, as before stated, to explain the action we have here assumed. It is observed, for instance, that the mortar beds are flat and sensibly level along their upper surfaces; that they are most pro-

nounced in coarse material, though often faintly traceable in fine, and yet that frequently they strike through these coarse beds, as indicated in the ideal section shown in fig. 306, leaving uncemented portions above and below. Coarse stream deposits rarely are uniform in thickness, since they are laid down in scour channels and are themselves in turn scoured in the process of the overplacing of other beds. And this disposition along level planes, with disregard of the complex gentle inclinations of structure surfaces, seems almost unavoidably to suggest standing water in the ground, at various levels successively, as the determining cause of deposition.

But as to how the ground water acts or is acted upon at its surface or water plane to bring about deposition, the writer has no explanation to offer. Professor Haworth suggests[1] that the mortar beds have resulted merely from the clogging, in time, of channels of free ground-water movement, the coarse beds constituting such channels. But this view does not take account of the fact that the cementation planes strike through the gravel beds with level upper surfaces, not occupy-

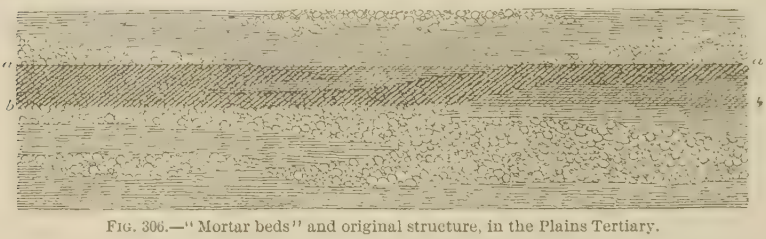
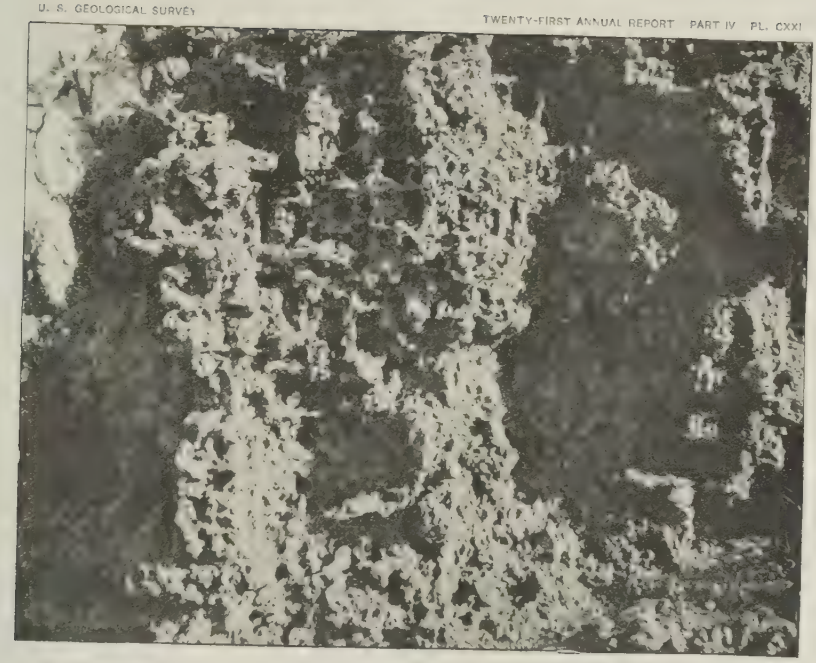


FIG. 306.—"Mortar beds" and original structure, in the Plains Tertiary.

ing their full thickness, nor that, on the other hand, the gravel beds frequently are free from cementation. Indeed, uncemented gravel courses are the main channels of circulation of the present ground water, so far as it has movement at all. At the same time they (coarse sand included) constitute the only ground of appreciable yield for wells; and since anywhere upon the High Plains, within a short horizontal range, yield to the well maker is practically assured at some depth, uncemented coarse beds must be of fairly common occurrence. It appears to be the fact that wherever along planes of cementation coarse material occurs, there binding has been sufficiently pronounced to produce "mortar beds," but that between such planes this open-textured material is rather more free from lime deposit than the fine.

There are several difficulties in the way of the supposition that the excessive lime accumulations of the mortar beds had their determining cause in fixed positions, successively, of the ground-water level. So far as they are exposed in natural section they are more or less in ruins, so that, as a rule, the level upper surface referred to is barely

[1] Univ. Geol. Surv. Kansas, Vol. II, 1897, pp. 270-271.



A MORTAR-BED STRUCTURE IN SAND

B. MORTAR-BED STRUCTURE IN SILT.

traceable. If the mortar bed represents secular lingering of the water plane at a general level, its thickness would seem to mark the vertical measure of the minor fluctuations of level at that position through short periods of groups of years. The upper surface would thus indicate an extreme range. It should therefore be of inferior hardness and durability. Possibly it is for that reason that it is rarely well preserved. Wherever any definite surface is even suggested, however, it seems to be level.

Finally, it is hardly more than to be inferred that mortar-bed formation is now in progress at the present water level. The inference merely seems to be reasonable. In this connection Professor Haworth says:[1] "In no instances known to the writer is the cement found in the same horizon with the ground water." He is here speaking of the records from a series of artificial sections—those of the "State wells" of western Kansas Presumably, however, he would not include in this statement his experience from observation of natural sections. At any rate, the present writer does not find that it applies generally. It will indeed rarely happen, in the case of well borings, that they will come upon the water plane in coarse material, for coarse material constitutes but a small part of the total mass. To be sure, from the well maker's point of view, it is in coarse material only that water is found at all. But he regards it as "found" only when it delivers freely. He takes no account of the water plane except as that plane is revealed by rise in his pipe, to a stand at some higher level, after the "vein" has been encountered. Virtually, anywhere in the Plains Tertiary, as shown, the well maker is assured of success at some depth, but he is not able to predict what that depth will be. Where in any neighborhood wells are bored close together, the depths to a suitable "flow" will greatly differ among them, though the pumping lift in all will eventually be from the same level. It would be rare fortune to the well maker to happen upon water in paying quantity i. e., from coarse sand or gravel—precisely at the pumping level. Therefore, since it is only in coarse material, as a rule, that the mortar bed is formed strongly, there would need to be a large body of evidence to the contrary to destroy the probability that such beds are now forming where the present water plane and coarse beds happen to coincide in position.

But while the writer has no explanation to offer as to the cause of lime deposition at the water plane, the assumption that it actually does occur, and that the mortar beds have their origin in this way, is supported by the fact that it occurs elsewhere under what appear to be essentially similar conditions.

For example, carbonate of lime is deposited about springs of exceptionally pure water rising from the bottom of Lake Mono, a Great

[1] Ibid., p. 267.

Basin lake without outlet, heavily charged with mineral salts. An analysis of the water from one of these springs is given by Prof. I. C. Russell, as follows:[1]

Analysis of water from a spring in Lake Mono.

Constituent.	Gram in a liter.
Silica (SiO_2)	0.0178
Calcium (Ca)	0.0414
Magnesium (Mg)	0.0044
Potassium (K)	0.0088
Sodium (Na)	0.0513
Sulphuric acid (SO_4)	0.0546
Chlorine (Cl)	0.0144
Carbonic acid (CO_3) by difference	0.0991
Total	0.2918

In "probable combination" Professor Russell gives: "Calcium carbonate ($CaCO_3$), 0.1035 gram in a liter." Commenting on these spring deposits, he says:[2]

At the western extremity of the lake are a number of springs, some of which are sublacustral. Two of special interest rise at the bases of tufa [carbonate of lime] crags at a distance of 20 or 30 yards from the lake. That they have been flowing for a great length of time seems evident from the fact that the tufa about them was deposited from waters issuing from the same orifices when the lake stood far above its present level. They are copious, each delivering perhaps 20 gallons of water a minute, but it was not practicable to measure their volume. They are clear and cool and evidently of exceptional purity. At the present time they are not depositing mineral matter. * * *

The positions of the springs rising in the lake near Black Point are indicated in calm weather by the eddies they produce on the lake surface. On rowing over these submerged springs we find that some of them rise from the tops of tufa crags which are covered by 10 or 12 feet of water. These crags are of the same character as those standing on the shore * * * and were formed by the deposition of calcium carbonate from the incoming waters. The submerged towers from which these springs issue are in some instances 8 or 10 feet in diameter and have a height of 20 or 30 feet. They are clustered in groups in the same manner as the tufa towers and castlelike masses mentioned above, which have been left exposed by the receding of the waters of the lake. Unlike the deposits that have been exposed to the atmosphere, their forms are unbroken, showing that the lake has never evaporated sufficiently to bring them above the surface or at least expose them for a long period. The upward rush of fresh water from the orifices in the summits of these sublacustral towers through the denser waters of the lake is in some instances sufficiently strong to deflect a boat when allowed to float over them. * * *

Other tufa domes similar to those we have mentioned rise above the surface of the lake near the shore. * * * They rise in water that is 10 or 12 feet deep to a

[1] Eighth Ann. Rept. U. S. Geol. Survey, Pt. I, 1889, p. 290.

[2] Ibid., pp. 289–290.

A.

B

CROSS BEDDING IN MORTAR BEDS.

height of about 12 feet above the lake surface. Many of them are vase shaped. * * * The tops of several are hollowed out so as to form basins, and in a few instances these depressions are filled with clear, fresh water that rises through the porous and tubular tufa composing the submerged shaft of the structure. These are typical specimens of sublacustral spring deposits which have been left partially exposed by a recession of the lake waters, but are still points of discharge for the springs that built them.

The water of one of these natural fountains, rising in a lake whose water is utterly undrinkable, is of exceptional purity [analysis given on preceding page]. * * *

Two analyses are given of the denser lake waters. One is as follows (p. 293):

Analysis of the water of Lake Mono.

Constituent.	Grams in a liter.
Silica (SiO_2)	0.2800
Calcium (Ca)	0.2900
Magnesium (Mg)	0.1300
Potassium (K)	1.1600
Sodium (Na)	18.9100
Sulphuric acid (SO_4)	6.8100
Chlorine (Cl)	12.1300
Boracic acid (B_4O_7)	0.1600
Carbonic acid (CO_3) by difference	11.9800
Total	51.8500

The second analysis, which "may be taken as approaching more nearly the average composition of the lake," gives a very slightly increased total of solids. The difference between the spring water and the lake water as to mineral matter in solution is in the ratio of about 1 to 200. But it will be seen from the above table that, as regards calcium, there is hardly any difference at all, the lake containing 0.2900 gram to 0.0414 gram in the spring; or, "in probable combination," as calcium carbonate, 0.6800 gram to 0.1035 gram. And the second analysis even reverses the order of difference, giving to the heavy lake water less of lime than is contained in this spring of "exceptional purity." Yet Lake Mono has made heavy deposits of calcium carbonate, and little else, though of sodium compounds it holds in solution several hundred times more than of this one compound of calcium.

Of the mineral matter in solution in rivers, on the average, Russell says:[1]

In both American and European river waters, so far as can be determined from the data at hand, the average of total solids in solution is 0.1888, and the average of

[1] Geological history of Lake Lahontan: Mon. U. S. Geol. Survey, Vol. XI, 1885, p. 174.

calcium carbonate 0.088765 part per thousand. These figures may be assumed to represent the average composition of normal rivers. It will be noticed that the average for calcium carbonate amounts to nearly one-half of that for total solids.

It will thus be seen that both the Mono spring and the lake itself carry less of calcium carbonate than average river water, the lake being fresher in this respect than the spring. Lime deposition, therefore, is not due to the presence of an unusual amount of lime in either the contributing spring or the water into which it flows.

The inference is that deposition of even the small amount present is due to the presence also, and in much greater quantity, of other mineral substances dissolved in the lake. Calcium carbonate is not only difficult of solution but difficult of retention in solution. The rivers tributary to Great Salt Lake, as shown by Mr. G. K. Gilbert,[1] carry somewhat more than the normal amount of calcium carbonate; yet no trace of it is to be found in the waters of the lake. Commenting on its absence, Mr. Gilbert says (p. 252): "Despite the fact that calcium carbonate is precipitated on the shore in the form of an oolitic sand, none of the analysts have succeeded in finding it in the brine. * * *" Great Salt Lake is much more heavily charged with mineral substances in solution than Lake Mono; presumably because of their presence the large quantity of lime carbonate contributed by its rivers is completely precipitated; and Mono precipitates its lime for the same reason, yet it retains a trace, because the difficulties in the way of retention are not so great as in the case of the heavier waters of Salt Lake. The tufa-crag accumulations around the Mono spring orifices are the more striking, but the distributed deposit in Salt Lake is the more complete. Here the dissolved impurities are 174.4 grams to the liter[2] (Mono contains but 51.9 grams per liter); the streams from which they are accumulated carry about 0.2 gram, on the average, of which more than half is calcium carbonate, and yet to the 174.4 grams this half contributes nothing.

"It is well known," as Mr. Gilbert says,[3] in discussing the composition of the lake water, "that the precipitation of certain substances from solution is favored by the presence of certain other substances. * * *" The comparatively fresh water of springs and rivers is caused to drop its light burden of lime upon contact with heavy waters. On the assumption that the mortar beds are sheets of cementation at the ground-water surface, it would seem to be highly probable that like action for the same reason occurs there.

The source of ground water is, in the main, the local precipitation upon the ground surface above it. But in the case of an aggradation plain upon which far-traveled streams are spreading and in part are

[1] Lake Bonneville: Mon. U. S. Geol. Survey, Vol. I, 1890, pp. 207, 253-254.

[2] Ibid., p. 253. Mean of five analyses made in the years 1850, 1869, 1873, 1885, and 1889, at different heights of the lake.

[3] Ibid., p. 204.

A. THIN MORTAR BED PRESERVING UPLAND SURFACE.

B. CARBONATE-OF-LIME GRAVEL.

becoming concentrated by evaporation, the ground water will receive some contribution heavily charged with concentrated solutions. We shall thus have at the water plane "fresh" water, lightly charged with lime carbonate, occasionally brought into contact with other strong solutions favorable to its precipitation. The High Plains are not an aggradation plain in process of building, but fragments of an old one, above the traversing mountain streams. They are not, therefore, receiving concentrated solutions from these streams, spreading upon them, as formerly. Presumably, in consequence, the formation of mortar beds at the present water-plane level is not so marked as formerly.

The desert débris plain may be regarded as in some degree the homologue of the inclosed desert-lake basin; it is the field of precipitation of lime from fluvial waters. Other dissolved materials of streams, equal in the sum of their volumes to the volume of the lime, are retained in solution in the ground water, or are picked up by re-solution after deposit, and ultimately are carried off by slow ground-water drainage. The lime precipitate alone remains. It becomes distributed throughout the mass during its building up. But especially it becomes concentrated, sufficiently to effect a fairly hard cementation at the ground-water level wherever it is extended through coarse material. And if that level fluctuates, with pauses, there results a corresponding series of hard beds, discontinuous horizontally, since the coarse material is not horizontally continuous, and irregularly spaced in vertical section.

HAY'S "GRIT" AND "MARL" FORMATIONS.

Professor Hay, accepting without question the theory of lacustrine origin for the great sheet of the Plains Tertiary, found in the marked contrast of its coarse material, in which the mortar beds are most strongly defined, and the much more extensive accumulations of fine material, apparent reason for separating the mass into two distinct formations, their periods divided by an interval of erosion. The earlier of these formations, to which he assigns all of the coarse sand, the gravel, and the mortar beds, he calls the "Tertiary grit;" the later one he terms "Plains marl." The marl overlies the grit. Each of the formations, again, he subdivides into beds, giving these distinctive names also.[1] He says:

> The circumstances that led to * * * the extensive lakes * * * are not discussed here. * * * The waters were charged with lime, and all the beds we have included in the term Tertiary grit were deposited. * * * The Tertiary grit filled all the valleys and covered most of the intervening spaces of the Cretaceous surface. * * * When these * * * deposits were completed and the relation in height of land and water was changed, drainage began again, * * * and we have

[1] Water resources of a portion of the Great Plains: Sixteenth Ann. Rept. U. S. Geol. Survey, Part II, 1895, pp. 569–572.

the period of mid-Neocene erosion [the interval of interruption of lacustrine history above referred to]. * * * Valleys [in the grit] were cut out in a great part of the plains region. * * * There was another change and the region was again covered with water, which deposited over all the plains a bed of marl, varying in thickness from 1 foot to 200 feet. * * * At the end or in the last phases of the plains marl the lakes or inland sea began to be drained again, * * * and we have the post-Neocene erosion. This has lasted to the present day. * * * In one place the plains marl is found resting upon the highest beds of the Tertiary grit. A short distance away * * * it is found resting on a lower bed of the grit, the surface of which is very uneven. Such conditions are to be seen in every valley of the district.

It will be seen that he does not regard the coarse beds as interbedded with the fine, and that he accounts for the presence of coarse material at shallow depths on the assumption that such occurrences mark the summits of the deeply eroded grit.

He gives vertical sections, showing the marl resting upon an eroded surface of grit, and the grit in turn upon an eroded Cretaceous floor. He also gives section records from a number of well borings[1], which are regarded as carrying the suggestion of two distinct formations. The two following are typical:

Section at well No. 43, Cheyenne County, Kansas.

	Feet.
Soil	3
Yellow soil (plains marl)	50
Sandy rock	10
Red clay, Sand, Quicksand, containing 20 feet of water	110
Total	173

Section at well No. 118, Wallace County, Kansas.

	Feet.
Soil	5
Creamy clay (plains marl)	23
"Magnesia"	4
Running gravel	16
Rock and sand, with 12 feet of water	84
Total	132

These and other well sections to which Professor Hay refers can hardly be said to justify his division of the Tertiary into two distinct "formations." They show, rather, an irregular distribution of soft and hard material, in beds, from top to bottom.

A section (p. 580) which, taken alone, would better have borne out his view, is made up from exposures "in the ravines of the south side of the North Platte, northwest of Ogalalla." It gives "170 feet of Tertiary marl," underlain by 220 feet in all of "grit;" in the main cemented; of varying coarseness; but with very little of fine material. The boring here did not reach to the floor. But "a boring * * *

[1] Water resources of a portion of the Great Plains: Sixteenth Ann. Rept. U. S. Geol. Survey, Part II, 1895, p. 583.

A. SPRING IN TERTIARY BLUFF WITH MORTAR BED AS FLOOR.

B. ARTESIAN SPRING IN TERTIARY BLUFF WITH MORTAR BED AS COVER.

C. SPRING AT BASE OF TERTIARY WITH RED BEDS AS FLOOR

19 miles east of Ogalalla * * * continues the section downward" with 100 feet of clay, containing "sand streaks, some several feet thick." It thus shows an exceptional thickness of what should be termed marl underlying the so-called grit.

So far as Professor Hay has shown, there is no essential difference in composition between beds of fine material deeply buried and other beds near the surface. There are occasional differences in color, but they appear irregularly and are not constant along definite horizons. The terms "marl" and "grit," then, it would seem, make groupings of the clay, sandy clay, and fine sand on the one hand, and of the coarse sand, gravel, and cobbles on the other, which are artificial and misleading. The fact appears to be rather that the finer materials make up the bulk of the mass, and that the coarser materials—the so-called grit—are here and there, at various levels and in comparatively narrow belts, extended through it.

Professor Hay describes the marl as "varying in thickness from 1 foot to 200 feet." He assumes for the grit an erosion surface with that range of relief. In other words, prior to the deposition of the marl under still-water conditions, the grit had been eroded by streams to depths in its larger valleys of 200 feet. This rather violent assumption is made on the evidence of the few scattered well borings of the date of Hay's investigations. With the multiplication of wells in later years the value of such evidence is destroyed. Often a new well, within a stone's throw of one which had indicated no gravel for 200 feet, will encounter within that depth several beds of coarse material. On the other hand, a new boring close to one which had stopped in gravel near the surface, seemingly indicating for that position the summit of the "grit" at that level, may miss all coarse masses and extend the whole distance to bed rock through fine material.

LATER VIEWS OF GILBERT AND HAWORTH.

Since Hay's investigation along the western Kansas border, Mr. Gilbert has studied the Tertiary in the Arkansas Valley in eastern Colorado,[1] and Professor Haworth over the whole of its extension in Kansas.[2] Mr. Gilbert's examination was detailed near the mountains, but toward the Kansas line it is described by him as a reconnaissance. So far as he observed the "upland sands and gravels," as he calls them, excepting where they border on Kansas, he pronounces them fluviatile in origin.

After describing the erosion of the Cretaceous floor, which preceded the beginning of the gravel accumulation, he says (pp. 575–576):

> Eventually the process of erosion was completely arrested, and processes of deposition took its place. This change was brought about by some modification of conditions

[1] The underground water of the Arkansas Valley in eastern Colorado, by G. K. Gilbert: Seventeenth Ann Rept. U. S. Geol. Survey, Part II, 1896.

[2] Univ. Geol. Surv. Kansas, Vol. II, 1897.

which is not yet clearly understood. Perhaps the plains region was depressed at the west, and the slopes thus rendered so gentle that the streams could no longer carry off the detritus which came from the mountains, and it was deposited on the way. Perhaps a barrier was lifted at the east, so that the base-level stood higher. Whatever the cause, the streams which flowed from the mountains onto the plains, and thence eastward across the plains, ceased to carve valleys in the region of the plains and began to deposit sediment. When they had filled their channels so that their beds lay higher than the neighboring country, they broke through their banks, shifting their courses to new positions, and they thus came to flow in succession over all parts of the plains and to distribute their deposit widely, so that the whole plain in the district here described was covered by sands and gravels brought from the canyons and valleys of the Rocky Mountains. * * * The range in observed thickness is from 50 to 200 feet.

The chief material is coarse sand, and this is arranged in irregular beds with much oblique lamination, such as ordinarily results from the work of streams. In the sand are occasional pebbles, and these are in places gathered into distinct beds of gravel.

Mr. Gilbert refers, without adverse comment, to the prevalent opinion of geologists that the formation, as it thickens eastward, is a still-water accumulation, in lakes; "but," he adds, "the principal work within the field of our reconnaissance appears to have been done by running water."

Professor Haworth, the following year, extended the examination eastward from the Colorado-Kansas boundary, where Mr. Gilbert had left it; and he reaches for the deepening mass in Kansas virtually the same conclusion that Mr. Gilbert had reached for its beginnings in Colorado. He says:[1]

The relative positions of the gravel, sand, and clay of the Tertiary over the whole of Kansas * * * correspond much better to river deposits than to lake deposits. The irregularity of formation succession, the limited lateral extent of the beds of gravel, clay, and sand, the frequent steepness of the cross-bedding planes, all correspond to river deposits, but are not characteristic of lake deposits. It is difficult to understand how such irregularity of material could have resulted if the Sioux Lake of King, or any other lake, had extended southward across the whole of the western part of Kansas, and had been a factor in the accumulation of the Tertiary materials. It is quite possible that during Tertiary time, in which there were so many changes in the velocity of the water carrying the sediments, lesser local lakes and lagoons and swamps and marshes may have existed in different places and for varying lengths of time. But when we consider the Kansas Tertiary as a whole and yet in detail, it must be admitted that the materials themselves have many indications of river deposits and very few of lake deposits.

The present writer has described the whole of the great plain of which the High Plains plateaus are but fragments as, in its original condition, an aggradation plain on a vast scale, built to a smooth but sloping surface by the subdividing, shifting, and alternately increasing and failing streams of a dry climate; the initiation of that building is attributed to change of climate from relative humidity to dryness, not to interference with stream grade merely, by deformation; and its present erosion, together with the several recorded interepochs of erosion,

[1] Univ. Geol. Surv. Kansas, Vol. II, 1897, p. 283.

grouped together in the Pleistocene, is attributed to climatic shiftings back toward humidity. The complex structure, finally—an uneven network of gravel courses and elongated beds of sand penetrating a mass of silt and sand-streaked clay—is described as the normal product of desert-stream work under constant desert conditions. The coarse material is not regarded as the product necessarily of strong-running streams, and the fine material of sluggish streams, in alternating epochs, either of humid and dry climate or of high and low inclination of slope, but as the simultaneous product of branching streams of the desert habit, here running in a channel and there spreading thinly. Thus the writer is in accord with Professor Haworth, in the view that the Plains Tertiary, at least within the field of this investigation, embracing the High Plains, is fluviatile in origin. He regards, however, as improbable Professor Haworth's further opinion, expressed below, that the inciting cause of the deep accumulation, burial, and plain building was increased precipitation, while the contrasts of coarse and fine in the materials used in the building, emphasized by sharply defined beds, are to be accounted for on the assumption of many deformations, up and down, tilting the plain alternately to steep and gentle grades. Professor Haworth says (pp. 13-14):

> During early Tertiary time the drainage seems to have been similar to that of the present. It is probable the climatic conditions were very different then from those now existing over the Great Plains. The vast amount of material carried eastward from the mountains and deposited in the plains from the Gulf of Mexico northward into Canada implies a correspondingly greater precipitation. There are good reasons for believing the mountainous elevation occurred with relative slowness, but with considerable irregularity. The evidence of this on the Great Plains is confined principally to the character of the materials transported. In some places heavy, coarse gravel beds were formed, the individual gravels in which frequently have a diameter as great as 4 or 5 inches, requiring a great velocity of water to transport them throughout the distance they have been carried. Above and below such gravel beds the material is frequently composed almost entirely of the finest sand and clay and silt, which strongly implies that the movement of the water at that time was not rapid, but rather that it was slow and sluggish.
>
> As is shown later in an article on the physical properties of the Tertiary, these heavy gravel beds and the beds of fine sand and clay alternate with each other, showing conclusively that there have been recurrences of conditions, a rapid movement of the water being followed by a slow one, which in turn was followed by another period of greater velocities. It therefore seems that the terrestrial movements were such, either in the mountains or the eastern part of the plains area, that the velocities of the mountain streams were changing alternately from slow to rapid and again from rapid to slow and sluggish.

The Tertiary plain, as we find it preserved in part in the extraordinary fragments of the central upland flats, seems to bear witness to long-enduring stability of climate, though a marked change of climate, with minor fluctuations, has in fact put an end at last to its building and is bringing about its degradation and removal. The gently graded extension of the plain to so great a distance seems to be evidence also of long-continued freedom from earth movement. Probably the

climatic oscillations which marked the Pleistocene, and not ground oscillations, are responsible for its complex channelings and refillings, since during the same period virtual freedom from ground oscillation is indicated in the Great Basin. But the construction of the great alluvial sheet probably marked the close merely of the Tertiary. The event is perhaps best to be regarded as pre-Pleistocene, and as having occurred during an episode of quiet following the orogenic movements which had either directly produced, or had initiated through erosion, notable topographic transformations both in the mountains to the westward and over the Cretaceous floor of the Plains.

Finally, the High Plains, of this fluviatile origin, exhibit an unfailing characteristic of desert alluvial accumulations in that the mass of their materials is impregnated and, as a rule, feebly stuck together with lime carbonate. Where, exceptionally, there is stronger cementation along definite horizons, giving origin to mortar beds, these seem to have been an after effect, occurring during the relatively humid period, with its minor climatic oscillations, and marking fluctuations of level of the ground water.

THE UNCEMENTED COARSE MATERIALS—THE "WATER-BEARING BEDS."

Mortar beds—i. e., beds of cementation—occur both above and below the present water plane. They occur, in fact, at all levels, but not all of the open-textured material of the sand beds and gravel courses, not even the greater portion of it, has been thus cemented and rendered impervious to water. These uncemented gravels, where they lie below the water plane, constitute the "water-bearing beds" —that is, they respond freely to pumping.

They are also the main channels of the present ground-water movement. Where they are cut across and exposed in section by stream canyons they afford means of relatively easy escape for the ground water. In other words, their exposures are marked by rapid drainage off, and such relatively rapid drainage constitutes the normal spring. The water plane is drawn down chiefly by this means. Erosion, with valley cutting, lowers the ground-water level, because these arteries are cut. It is not lowered to the stream level of the dissecting valley, but as a rule lingers well above it, because the gravel courses are not true arteries—are not unbroken for long distances—and connect with one another often only by smaller veins, or not at all. However, it is through such imperfect and complex connections as the gravel courses have that the ground water is drained.

It will thus be recognized that the well, in order to have large delivery, must be in liberal communication with the gravel courses, and that in order to secure the best possible results it must intersect them at as many levels as possible.

A.

B

BASE OF TERTIARY.

CHAPTER III.

DEFICIENCIES OF CLIMATE.

The climate of the High Plains is described as subhumid. It is variable, from humid to arid, but in the mean annual precipitation there is a marked deficiency. The High Plains are a region of droughts, though not of perpetual drought, since there are humid intervals, in short periods of groups of years; but the mean annual fall is below what is requisite for successful agriculture. Among the periodic variations those of marked deficiency have the longer duration. Yet the humid intervals have enabled the pioneer to achieve a result sufficient to hold out to him the hope, hardly even yet wholly abandoned, that they indicated permanent change of climate.

The extensive western movement of settlers within the trans-Mississippi section some years ago was influenced in a great measure by several successive years of abundant rainfall. There was an undercurrent of opinion, moreover, that the increased rainfall was in some measure due to the permanent occupation of the major portions of eastern Kansas, Nebraska, and adjacent States by an agricultural population. It was argued, and with some show of reason, that the breaking up of the prairie sod and the cultivation of the soil over such a large extent of territory must increase local evaporation and, consequently, the rainfall.[1]

But the records of precipitation within this section, extending over a quarter of a century, disclose several of these humid episodes, offset always by periods of desert dryness, and indicate in the long run climatic stability.

In an arid climate the agriculturist looks upon the rainfall as practically negligible; his dependence is wholly upon irrigation. So far as benefit to growing crops is concerned, the Arid Region may be regarded as virtually without rainfall. In like manner the relative term "subhumid" has come practically to signify a climate in which the natural moisture supply, from rain and snow, falls a little short of what is necessary for agriculture without irrigation. Hence, in a subhumid region provision must be made for at least supplemental irrigation; and the necessity for resort to such artificial aid will be imperative most of the time and advantageous always.

It is the experience everywhere in arid lands that the percentage of arable land that is irrigable—that is, for which water for irrigation is obtainable—is comparatively very small. Values rest much more in

[1] Rainfall of the United States, by Alfred J. Henry: Bull. D, U. S. Weather Bureau, 1897, p. 9.

available water than in land. The arable, but nonirrigable, land is in abundance. The subhumid country, on the other hand, has the advantage of a nearly sufficient precipitation to build upon, so that a given amount of water for irrigation will serve a notably larger area. It is apparent from the records of precipitation on the High Plains that the natural supply would need only to be slightly supplemented to render their entire vast area highly productive. If, however, that small additional supply is not to be had, the High Plains are irreclaimable for agriculture.

FACTORS WHICH MAKE UP CLIMATE.

The factors which, from the point of view of the farmer, go to make up climate are not only precipitation and its distribution throughout the year. The barren Staked Plains of Texas have a precipitation fully equal to that of the major portion of the wheat lands of the Dakotas, and it is of the same type of monthly distribution; but they are in effect much drier, since other conditions, conducing to greater evaporation, notably reduce the soil moisture available for growing crops. These other conditions are: (1) A more spasmodic character of the summer rains, favoring evaporation as against soil absorption; (2) a higher temperature, resulting in a lower "relative humidity," though the absolute humidity or actual moisture content of the air may be higher; (3) more hours of sunshine; and (4) a greater wind movement.

The meteorological records of the United States Weather Bureau afford abundant data for a statement, sufficiently definite for present purposes, of the climate of the High Plains, expressed in terms of normal precipitation, temperature, relative humidity, sunshine and cloudiness, wind movement, and evaporation, both averaged for the year and, what is of much more practical interest, presented for the crop-growing season only. At the same time they show that the changes of climate, which on several occasions have extended the humid area nearly to the foothills of the mountains, and again have contracted it, to the serious injury of established farming interests to the eastward, are but oscillations across a stable mean and have fairly definite periods.

PRECIPITATION.

The Weather Bureau has maintained record stations upon the High Plains at Dodge, Kansas, since 1874; at or near Amarillo, Texas, since 1879; and at numerous other points for shorter periods. We thus have a daily record, among other factors, of precipitation (rain and melted snow) extending over a quarter of a century.

PRECIPITATION BELTS OF THE GREAT PLAINS.

These records of a quarter of a century show uniform decline in precipitation across the Great Plains westward, with rise again to comparative humidity locally in the Rocky Mountains. Upon a climatic map this gradation in precipitation might be represented by north-south belts, indicating four subdivisions westward, as humid, subhumid, arid, and, again, subhumid. The High Plains would be seen to be included within the second or subhumid subdivision. As a topographic zone of virtually no erosion this region of flat uplands would show fading off on the west into the eroded country of the arid belt, but abrupt termination on the east along a much-indented escarpment, well within the subhumid limits. The remaining strip would represent a zone of sharp erosion—a zone of capture by headwater sapping on the part of the multitude of streams of the humid belt. Fig. 307, in section along the slope of the Great Plains, shows the High Plains as a broad terrace of survival within the belt of medium precipitation.

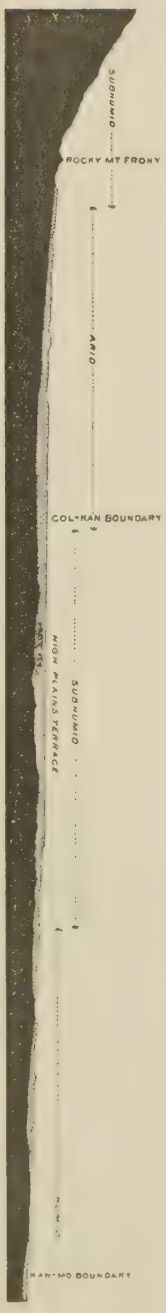


FIG. 307.—West-east section of Great Plains, showing climatic banding and relative position of High Plains terrace.

But a map which should show precipitation only would not be complete as a climatic map. To the northward upon the Great Plains it would not be even approximately accurate. For example, precipitation on the Staked Plains, as represented by the eighteen-year record at the Amarillo station, in the center of the Panhandle of Texas, is 21.94 inches; at Garden, midway across the High Plains, in central-western Kansas, it is 17.38 inches; at Goodland, northwestern Kansas, at about the northern limit of the High Plains, it is approximately 21 inches; while in central North Dakota it is but 18 inches, and at St. Vincent, near the northeastern corner of that State, in the center of a great wheat-growing region, it is only 19.5 inches. In short, the vast barren flats of the High Plains have a slightly greater precipitation than even the major portion of the wheat lands of the Northwest. The precipitation belt, which across western Texas and Kansas includes the High Plains, and is subhumid there, becomes, in effect, humid to the northward and is included within the agricultural area. Its eastern boundary swings gradually eastward, while

the western limit of agriculture crosses it, swinging westward. The west-east section shown in fig. 307 is along the parallel of the Arkansas River in western Kansas. So far north as the boundary between the two Dakotas the wheat-growing area would be found to have completely overlapped the precipitation belt, which, south of the Arkansas River, is, in effect, too dry for agriculture without irrigation. The water of rain is in each case the sole reliance, and there is an appreciably greater fall, annually, to the south than to the north; but taking account also of the distribution of the fall throughout the year, and of those factors which make for loss from the soil, it will appear that the somewhat smaller precipitation northward is much the more effective.

PRECIPITATION OF THE CROP-GROWING SEASON.

In his Rainfall of the United States[1] Professor Henry introduces "a departure from the usual methods" by presenting separately, as of more vital interest to agriculture, the precipitation of the crop-growing season. This season he regards as comprising the half year from April to September, inclusive. He says (p. 11): "Tables of annual precipitation tell us how much rain or snow falls on the average during the course of the year, but they afford no indication, directly or indirectly, as to whether the rain comes when it will be of the greatest service to agriculture or whether it falls after the time of maturity of the staple crops." In illustration of the importance of this separate presentation, he divides the precipitation of the United States into "types of monthly distribution," by districts, showing the ratio of the seasonal fall to the annual fall, in diagram form, by monthly percentages of the total. From this showing it appears that while the distribution of precipitation throughout the year is fairly uniform in the States along the middle Atlantic, in New England, in the Ohio Valley, and along the border of the Great Lakes, it is strongly concentrated in the summer months upon the Great Plains. On the other hand, it shows a pronounced maximum during the winter season in the Great Basin, where summer rains are most needed. At Winnemucca, Nevada, near the center of the Great Basin, the midwinter (January) fall is nearly twelve times that of the midsummer (July) fall, with a fairly uniform gradation between extremes, while the Great Plains, with a more evenly graded annual variation, shows a difference between the records of these months in the ratio of about 5 to 1, on the average, the other way.

Selected from Professor Henry's diagrams, fig. 308 strikingly illustrates, by contrast, at four widely separated points in the United States, these types of monthly distribution of precipitation. Lawrence, Kansas, is chosen as representative of the Great Plains. Though

[1] U. S. Weather Bureau, Bulletin D, 1897.

the total precipitation here is above the average of that for the Plains in general, in its monthly variation it is typical of the whole. It will be seen that the distribution, as regards the crop-growing season, is especially fortunate.

A more striking comparison can be made if extremes be taken. Garden, in western Kansas, is upon the High Plains; Winnemucca,

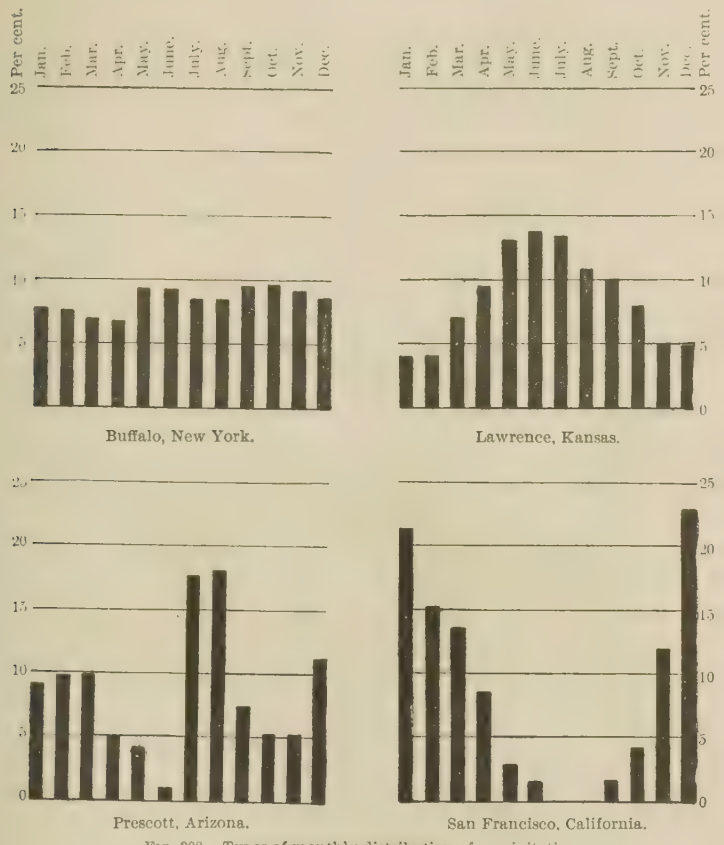


FIG. 308.—Types of monthly distribution of precipitation.

Nevada, is about centrally placed in the Great Basin desert. The mean annual fall at Winnemucca is 8.5 inches. The fall during the half year from April to September, inclusive, is but 2.9 inches. At Garden the record is 17.4 inches for the year, of which 14.1 inches are credited to the six months from April to September, leaving for the nongrowing season a lighter fall than during the same period in even arid Nevada. The "mean annual" record greatly overstates the effective precipitation for arid Nevada, while it understates it for the

subhumid High Plains. The complete monthly records at the two points are as follows:

Locality.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	The year.
	In.	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*
Winnemucca..	1.2	0.9	1.0	0.9	0.9	0.6	0.1	0.1	0.3	0.6	0.8	1.1	8.5
Garden.....	0.4	0.7	0.5	1.1	2.5	3.8	3.3	1.9	1.6	0.6	0.4	0.6	17.4

Obviously a fairer comparison would be the following:

Locality.	Apr.	May.	June.	July.	Aug.	Sept.	Apr. to Sept., inclusive.
	In.	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*
Winnemucca..	0.9	0.9	0.6	0.1	0.1	0.3	2.9
Garden.....	1.0	2.5	3.8	3.3	1.9	1.6	14.1

The disparity is in fact much greater than appears from an examination of the two annual records, and is brought out only by comparison of the crop-season records. It is not fully expressed even then, since the evaporation at Winnemucca is 50 per cent greater than at Garden.

It is in such manner that comparison should be made between the climate of the High Plains and that of the humid region to the eastward. St. Louis, at the eastern margin of the Great Plains, is nearly due east of Garden. The mean annual temperature and the evaporation rate at the two points are about the same. Their precipitation records compare as follows:

Locality.	Jan.	Feb.	Mar.	Crop-growing season.						Oct.	Nov.	Dec.	The year.	Apr. to Sept., inclusive.
				Apr.	May.	June.	July.	Aug.	Sept.					
	In.	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*
Garden	0.4	0.7	0.5	1.1	2.5	3.8	3.3	1.9	1.6	0.6	0.4	0.6	17.4	14.1
St. Louis	2.2	2.7	3.4	3.7	4.7	5.0	3.8	3.5	3.1	2.8	3.1	2.8	40.8	23.8

In his Rainfall of the United States Professor Henry gives charts not only of the mean annual precipitation, but of the precipitation from April to September, inclusive, separately.

It is not to be understood, of course, that the out-of-season fall contributes nothing to the moisture supply of plant growth. It wets the soil, and comparatively little of it is lost through evaporation before the advent of warm weather. It contributes to soil moisture. But mainly it soaks downward, beyond the reach of plant roots, and its larger contribution is to the ground water. Compared with the summer rains, it plays a small part.

SPASMODIC CHARACTER OF THE SUMMER RAINS.—"STORM TRACKS."

The most effective rains are those which fall slowly and are followed by lingering cloudiness. There is then a maximum of ground absorption and a minimum of evaporation. Such rains, as a rule, are widely distributed and occur mainly along recognized "storm tracks." The rains of the High Plains are rarely of this character. The normal "cyclonic" storms cross these uplands in winter only. The summer rains have the character of abrupt, heavy, and brief downpours, are local, and have short and erratic courses. They are usually accompanied by hail, and often do damage to crops from this cause, and accomplish only a minimum of good, owing to their violent character in general. Furthermore, though they are of frequent occurrence during the growing season, considered for any large area as a whole, the distribution of moisture is unequal locally, and their wandering and crossing tracks may here and there leave small areas very lightly watered or even wholly unvisited.

In his introduction to the general subject of rainfall, in the volume already referred to, Professor Henry says:

> Cooling by expansion as air ascends is one of the most effective causes of rainfall. The ascensional movement of air is brought about in several ways, chief of which are: (1) The air may be forced up the side of a mountain into a region of diminished pressure and lower temperature, as happens whenever a mountain range runs in a direction at right angles to the prevailing winds. (2) In the warm season the lower layers of the atmosphere, under the effect of solar radiation and probably other causes, frequently reach a state of unstable equilibrium, thus inducing ascensional currents. Summer thunderstorms are largely a result of this process. (3) Last, and doubtless most important of all, is the circulation of air in cyclonic storms, viz, a radial inflow from all sides and an ascensional movement in the center. A very large percentage of the rain of the United States is precipitated in connection with the passage of storms of the latter class.

The summer rains of the High Plains belong almost wholly to class 2.

The principal tracks of the cyclonic storms of the United States are either to the north or to the south, but mainly well to the north. A few cross the northern end of these uplands in April, September, and November. During the ten years from 1878 to 1887, inclusive, the United States Weather Bureau made this matter of storm tracks the subject of a special investigation, and in the resulting publication[1] these facts are elaborately exhibited by means of charts.

It appears that not only are there many more storm tracks to the northward, but that storms follow one another along these northern tracks with the greater frequency. "More than half of the August storms begin and move along the northern circuit, like beads on a string, with great regularity. The breadth of the track covered by them is about 400 miles. This accounts for the fact that in the Northern

[1] U. S. Weather Bureau, Bulletin A, 1893.

States the alternation of warm and cool days takes place with wave-like regularity, while in the Southern States the temperature is almost uniform * * *."[1]

A cyclonic storm may or may not be accompanied by precipitation at all points along its course. A storm is essentially an atmospheric disturbance; precipitation is an incident. The great bodies of moisture-laden air which pass eastward across the Plains (and all storm movement is in that direction) retain their moisture in large measure until that passage is nearly completed. It is because of local conditions effecting this result, and not because the air of the Plains is, strictly speaking, dry, that the fall there is light.

The figures on the Weather Bureau charts indicating storm frequency take no account of sporadic and local storms. These occur mainly out of the paths of the great cyclonic movements. The figures show that the frequency of cyclonic storms increases rapidly to the northward. At the northeastern corner of North Dakota, in the center of a great wheat region, the number is 30 annually. At the center of the Staked Plains of Texas it is 9 annually. During the crop-growing season the figures for the northern point remain proportionately large, while for the Staked Plains they drop to almost nothing; and yet the precipitation at these two points is about the same, both annually and during the summer months.

The purpose of this discussion is to bring out the fact that the character of the precipitation, especially during the half year from April to September, inclusive, for the High Plains and for the Plains to the northward is radically different; that for the High Plains it is of the local, brief, and heavy thunderstorm variety, and that this characteristic constitutes for them a defect of climate.

By way of summary of the foregoing the following extracts are made from the text accompanying the storm-track charts above referred to.[2]

The principal track of winter storms over the North American continent is traced eastward from the Pacific to the Atlantic ocean between the forty-fifth and fiftieth parallels [central through North Dakota]. * * * For the spring months the average track of storms * * * is farther south than during the winter season. The principal track is traced eastward between the fortieth and forty-fifth parallels [central through Nebraska]. * * * In April the region of greatest storm frequency * * * occupies an area extending from the middle Missouri Valley over the middle-eastern slope of the Rocky Mountains, where the average number of storms is in excess of three. [These touch only the northern end of the High Plains.] * * * In the summer season storms seldom cross the western mountain ranges of the North American Continent. A large majority of the storms of those months originate on the middle and northeast slopes of the Rocky Mountains, advance toward Lake Superior, and pass thence to the Gulf of St. Lawrence. * * * In autumn the principal storm track * * * crosses the Pacific coast between the mouth of the

[1] Storms, storm tracks, etc., by Frank H. Bigelow: U. S. Weather Bureau, Bulletin 20, 1897, p. 14.
[2] U. S. Weather Bureau, Bulletin A, 1893, p. vi.

Columbia River and the fifty-fifth parallel, and east of the one hundredth meridian passes almost due east between the forty-fifth and fiftieth parallels [central through North Dakota]. * * * These figures show that the stormiest latitudes are between the forty-fifth and fiftieth parallels * * * and that the number of storms decreases rapidly north and south of those latitudes. * * * A study of the storms of the Northern Hemisphere shows that the longer-lived storms commonly originate in the higher latitudes. The storms which appear on the Pacific coast north of Washington possess greater vitality than any other class of storms traced over the Northern Hemisphere.

SECULAR VARIATION OF PRECIPITATION.—DROUGHTS.

Of hardly less importance than the normal precipitation, in the verdict of the agriculturist against the climate of the High Plains, is its variability from year to year, and the occurrence and duration of droughts. On this point the Weather Bureau records again afford fairly satisfactory data. The record at Dodge, western Kansas, covers a twenty-five-year period. "* * * At least thirty-five or forty years' continuous observations are required to obtain a result that will not depart more than ±5 per cent from the true normal, even if the register be continued indefinitely. The average variation of a twenty-five-year period is about ±5 per cent, and of a forty-year period about ±3 per cent; that is to say, if any period of twenty-five years be selected from a register extending over eighty years, the average of the twenty-five-year period may be 5 per cent above the true normal, or it may be 5 per cent below it."[1] The Dodge record, therefore, can be relied upon within 5 per cent for exhibition of departures from the normal during the last quarter century. The position of this station is at the eastern margin of the High Plains, about 160 miles to the south of their northern termination. The Amarillo station, with an eighteen-year record, is in a northern-central position upon the Staked Plains of Texas.

[1] Rainfall of the United States, by Alfred J. Henry: Bull. D, U. S. Weather Bureau, 1897, p. 10.

The following are the records at these two stations, averaged by months:

Precipitation at Dodge, Kansas.

[In inches.]

Year.	Jan.	Feb.	Mar.	Crop-growing season.						Oct.	Nov.	Dec.	Annual.	Departure from normal.
				Apr.	May.	June.	July.	Aug.	Sept.					
1874..	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.22	0.23	0.05	.....	.....
1875..	0.12	0.10	0.04	0.72	2.26	0.73	3.28	2.06	1.32	0.06	0.00	0.09	10.78	− 9.60
1876..	0.00	0.05	3.59	0.16	1.15	2.53	2.26	1.03	2.13	1.00	1.35	0.15	15.40	− 4.98
1877..	0.18	0.56	0.25	3.38	4.96	3.92	1.79	4.09	0.50	3.34	0.56	4.36	27.89	+ 7.51
1878..	0.21	1.13	1.01	1.06	4.63	2.19	1.61	4.48	0.76	0.09	0.60	0.19	17.96	− 2.42
1879..	0.87	0.08	0.17	0.40	0.90	4.40	3.90	3.75	0.80	T.	0.04	0.12	15.43	− 4.95
1880..	T.	T.	0.04	0.11	3.01	1.59	4.00	5.17	0.32	1.42	2.43	0.03	18.12	− 2.26
1881..	0.15	1.63	0.50	2.38	12.82	1.77	5.06	2.36	3.13	2.19	0.95	0.61	33.55	+13.17
1882..	0.52	0.22	0.24	0.68	3.87	1.51	3.04	1.07	0.15	1.62	0.11	0.11	13.14	− 7.24
1883..	0.44	1.42	0.42	2.40	5.41	4.31	2.61	5.66	1.32	3.32	0.12	1.07	28.50	+ 8.12
1884..	0.08	0.28	1.91	1.07	4.47	7.67	6.40	4.82	0.23	1.50	0.83	1.10	30.36	+ 9.98
1885..	0.52	0.47	0.75	1.39	4.07	2.02	6.03	1.80	3.48	1.06	0.36	1.76	23.71	+ 3.33
1886..	1.82	0.46	1.50	1.90	0.40	5.47	2.07	2.46	2.33	0.45	0.24	0.25	19.35	− 1.03
1887..	0.07	0.53	0.17	2.46	3.69	4.00	1.00	2.28	0.14	0.48	0.35	0.54	15.71	− 4.67
1888..	0.23	0.73	0.93	4.08	2.86	5.16	4.07	3.00	0.78	0.81	0.06	0.23	22.94	+ 2.56
1889..	1.69	0.34	1.38	2.12	1.54	3.43	2.02	2.14	0.86	2.88	0.77	0.00	19.17	− 1.21
1890..	0.42	0.39	0.05	2.90	1.19	1.00	0.22	3.45	0.57	0.89	0.50	0.14	11.72	− 8.66
1891..	0.98	0.27	3.32	2.76	3.36	6.27	5.16	1.36	4.56	3.33	0.12	0.85	32.34	+11.96
1892..	0.25	1.01	2.62	0.40	3.23	3.34	0.66	4.69	1.04	0.73	0.31	1.38	19.66	− 0.72
1893..	0.02	0.34	T.	0.04	1.31	0.76	3.32	1.82	1.74	0.25	0.42	0.10	10.12	−10.26
1894..	0.04	1.03	0.40	1.88	0.95	2.80	2.05	0.15	2.03	0.62	0.03	0.62	12.60	− 7.78
1895..	0.58	2.26	1.31	0.91	0.97	5.32	4.84	2.42	0.06	1.09	0.34	0.21	20.31	− 0.07
1896..	0.49	T.	0.25	5.50	1.13	1.98	5.41	0.73	1.06	2.45	0.34	0.53	19.87	− 0.51
1897..	1.44	2.38	0.26	3.21	1.49	2.31	3.91	3.06	0.60	2.66	0.06	0.20	21.58	+ 1.20
1898..	1.74	0.70	0.24	0.97	10.31	4.57	3.14	2.26	3.16	1.87	0.96	1.54	31.46	+11.08
Means	0.53	0.68	0.89	1.79	3.33	3.29	3.24	2.75	1.38	1.37	0.48	0.65	20.38	.....

During the years in which the precipitation is above normal the excess is, on the average, 7.66 inches; during the years in which it is below normal the average deficiency is 4.15 inches; but the number of years of excess were only nine, while those of deficiency were sixteen. That is to say, low as the normal is, two years out of three will be below it; but not two out of every three. Changes are cumulative and exhibit a tendency to rise and fall by slow fluctuation, so that the wet years and the dry years are grouped. The rise is so high during wet years that there is a sufficiency for all agricultural needs. The climate becomes, in fact, humid. The universal green, over tilled and untilled areas alike, during these brief intervals of plenty, is irresistibly alluring to the home seeker, and invariably induces a return wave of population, which as inevitably ebbs back, however, during the following long period of drought.

Precipitation at Amarillo, Texas.

[In inches.]

Year.	Jan.	Feb.	Mar.	Crop-growing season.						Oct.	Nov.	Dec.	Annual.	Departure from normal.
				Apr.	May.	June.	July.	Aug.	Sept.					
1879..	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.10	.....	– (?)
1880..	T.	0.05	0.40	0.16	4.48	4.50	2.11	1.70	0.54	2.40	0.10	0.35	16.79	– 5.15
1881..	0.47	0.74	T.	1.26	5.27	0.10	3.28	0.49	3.18	0.69	0.42	0.26	16.16	– 5.78
1882..	0.33	0.16	0.53	0.66	7.48	1.54	5.65	1.55	3.18	2.32	0.96	0.40	24.76	+ 2.82
1883..	T.	0.53	0.04	0.82	4.56	1.66	2.87	6.56	4.97	5.32	0.04	0.84	28.21	+ 6.27
1884..	0.61	0.27	0.34	1.08	6.29	6.86	1.29	5.60	0.84	5.54	2.14	3.05	33.91	+11.97
1885..	0.45	0.87	1.86	4.67	7.23	9.82	3.62	4.94	0.65	0.60	0.25	2.11	37.07	+15.13
1886..	0.62	1.44	1.49	2.44	0.23	3.45	1.50	4.57	3.00	5.04	0.18	0.09	24.05	+ 2.11
1887..	0.01	0.06	0.19	6.06	7.01	2.39	0.92	3.52	1.67	0.69	0.23	0.08	22.83	+ 0.89
1888..	0.32	0.61	0.40	2.69	3.19	1.34	2.50	2.27	0.71	0.85	0.79	0.84	16.51	– 5.43
1889..	1.63	0.89	1.28	4.86	0.72	1.64	0.88	1.83	1.94	2.99	0.74	0.00	19.40	– 2.54
1890..	2.40	0.01	0.02	3.94	1.69	1.71	0.88	2.89	0.05	.....	.....	.....	.....	– (?)
1891..	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1892..	0.42	0.57	2.10	0.21	2.70	1.49	1.85	1.93	0.24	2.85	0.16	1.08	15.60	– 6.34
1893..	0.09	2.03	T.	0.16	2.19	2.03	2.05	2.67	5.27	0.03	0.28	0.43	17.23	– 4.71
1894..	0.02	1.15	0.05	0.85	1.30	3.59	1.82	3.41	2.11	0.39	0.00	0.82	15.81	– 6.13
1895..	1.60	1.92	0.16	1.31	1.78	6.84	2.88	3.87	0.57	2.26	0.81	0.79	24.79	+ 2.85
1896..	0.76	0.41	0.21	1.95	2.20	2.31	7.04	0.63	2.45	3.09	0.35	2.88	24.28	+ 2.34
1897..	2.26	0.65	0.47	1.08	4.44	2.32	2.16	2.71	0.73	1.63	0.08	0.63	19.16	– 2.78
1898..	0.86	0.82	0.35	0.98	3.52	4.81	3.88	4.03	0.48	0.41	0.34	2.06	22.54	+ 0.60
Means	0.71	0.73	0.55	1.95	3.68	3.24	2.62	3.06	1.83	2.18	0.46	0.93	21.94	.....

The record of these eighteen years on the South Plains shows as many years of excess as of deficiency, and the duration of the periods of each is the same; but they are long periods. Precipitation was above the normal from 1882 to 1887, inclusive—six years—and below the normal from 1888 to 1894, inclusive—six years also. If the alternation from wet to dry were in single-year periods, a wet year always following a dry one, agriculture might, perhaps, adjust itself to such severe conditions; but it can not hope to adjust itself to a condition in which a few years of prosperity, that is only moderate at best, is followed by several years of drought, with no production whatever, in recurring periods.

Comparison of the records at these two stations, 200 miles apart upon the High Plains, shows only a very rude correspondence between their wet and dry periods. There is closer correspondence between the records of stations near together, as, for instance, those of Dodge, Garden, Fort Wallace, and Goodland. But these show irregularity in detail, and for this the local character of the precipitation is doubtless in large measure responsible. Heavy summer rains, with paths narrower than the distance between any given pair of stations, may take such courses with reference to those stations as to render their records unrepresentative, as compared by single years, of the areas for which

they have to serve. But such records will be fairly representative as compared for long periods. They will be found to afford at least a suggestion of secular variation.

In a careful discussion of this question, drawing upon the records of the Weather Bureau, from its beginning, for the entire United States, Professor Henry shows[1] that while there is but faint suggestion of periodicity for the country as a whole, yet if the country be divided into districts, according to climatic types, periodicity will be found to be better defined in all and even strongly defined in some. For example, he says (p. 19): "The South Atlantic and Gulf States, in particular, show a marked deficit throughout almost the entire period [the ten years 1887–1896]. This fact naturally suggests an inquiry into the rainfall of the preceding ten years. The following statement shows the average precipitation at the principal Weather Bureau stations in the region just mentioned for twenty consecutive years in periods of ten years each:

Average annual precipitation in periods of ten consecutive years, 1877–1886 and 1887–1896.

Stations.	Average 1877–1896.	1877–1886.	1887–1896.	Difference.
	Inches.	*Inches.*	*Inches.*	*Inches.*
Lenoir, N. C	50.09	51.40	48.78	— 2.62
Hatteras, N. C	65.58	73.41	57.76	—15.65
Wilmington, N. C	53.06	58.83	47.30	—11.53
Charleston, S. C	54.59	56.82	52.37	— 4.45
Augusta, Ga	46.99	46.53	47.44	+ 0.91
Savannah, Ga	49.83	50.91	48.75	— 2.16
Jacksonville, Fla	53.40	57.69	49.12	— 8.57
Mobile, Ala	62.67	66.61	58.73	— 7.88
Montgomery, Ala	50.97	52.04	49.90	— 2.14
Vicksburg, Miss	54.37	62.04	46.69	—15.35
Memphis, Tenn	52.77	56.76	48.78	— 7.98
New Orleans, La	58.81	61.34	54.28	— 7.06
Shreveport, La	47.34	54.26	40.42	—13.84
Galveston, Tex	46.18	52.40	39.96	—12.44

And again (p. 22): "In the Ohio Valley there appears to be a rough periodicity of about nine years. Thus there were periods of heavy rainfall about 1837, 1847, 1858, 1866, 1875, 1882, and 1890, and of drought in 1839, 1856, 1863, 1871, 1878, 1886, and 1895."

In other districts the records are more confused. Possibly the explanation lies in the local conditions which determine the subdivision into types. The facts of importance in the present connection are,

[1] Rainfall of the United States, pp. 18–24.

however, that the full record of the climate of the country as a whole shows that it is in the long run stable; that since the climate of a geographic subdivision does not change without change of the whole, the climate of the High Plains may be assumed to be stable, in spite of their short record mainly showing instability; and that this minor instability amounts to another defect of their climate, since the wet years do not produce in superabundance, having only a bare sufficiency of moisture, and there is no compensation, therefore, for the years of drought.

EXCESSIVE PRECIPITATION.

Under this head Professor Henry says:[1] "Excessive rains naturally fall into two broad classes: (a) Rains of great intensity and short duration, and (b) light intensity and long duration. * * * The great majority of excessive rains (class a) in the United States occur east of the one hundred and fifth meridian, and principally in the summer months. They are most frequent in connection with summer afternoon thunderstorms." * * * These are the sporadic and local storms especially characteristic of the High Plains. They are excessive merely as to their rate of fall, and, as already stated, have diminished efficiency on that account.

TEMPERATURE.

The records of the Weather Bureau afford abundant data also for comparative statement of normal temperatures over the Great Plains region, both for the year and for the crop-growing season separately. While there is remarkably uniform increase of temperature northward, on the eastern Plains, the isotherms (lines of equal temperature) turn southward upon the High Plains subdivision, especially during the crop-growing season, indicating for that region a nearly equable temperature. That is, during the summer months the line of 65°, for example, passes nearly north-south along the High Plains. The normal crop-season temperature of North Dakota, on the other hand, is 10 degrees higher. This means a progressive diminution of evaporation to the northward, and a notably greater effective humidity in the Dakotas, though, as we have seen, the precipitation there averages slightly less than upon the High Plains.

"RELATIVE HUMIDITY."

The use in meteorology of the term "humidity" is more special than its popular use; as when, for example, to illustrate from extremes, we characterize the climate at St. Paul, in the Upper Mississippi Valley, as humid, and the climate at Yuma, in the Colorado desert, as arid. The normal precipitation at Yuma during the half year, April to September, is hardly more than a trace—0.5 inch; at St. Paul it is

[1] Rainfall of the United States, pp. 52–53.

20.4 inches; and yet the air of this virtually rainless desert contains, absolutely, 0.13 per cent more moisture than that of the highly fertile agricultural basin of the Upper Mississippi. What is known in technical language as its absolute humidity, or actual moisture content, is, during the half-year period mentioned, 0.13 per cent greater. In the month of June it is 1.38 per cent less, but in August it is 1.47 per cent greater.

At the same time, however, its capacity for moisture is greater and in much larger measure, so that comparing the actual moisture content at Yuma, large though it is, with what it might be if the air there were charged (other conditions remaining normal) to its full capacity, or "saturated," and making a like comparison for normal conditions at St. Paul, it appears that the air of the desert region is much further from a condition of saturation than that of the humid region. The latter region is in effect, or relatively, much more humid.

Among the elements which contribute to precipitation, this moisture content of the air (except as precipitation for the time being reduces it) is its most stable feature. Other elements, among which in this connection temperature is the most important, are comparatively very variable through short periods of time. But they vary without affecting the moisture content, except as they may cause it to precipitate a portion, and thus reduce it, by lowering the level, as we may say, of the capacity of the air for holding moisture to and below the level of the quantity it actually contains. This capacity is increased or diminished as temperature rises or falls. But it is the capacity only, not the actual quantity of water vapor in the air, which is thus varied.

The normal moisture content at Yuma, as we have seen, is high, somewhat higher even than that at St. Paul, but the normal temperature, and in consequence the possible moisture content, is very high. At Yuma it rarely happens that the variation of temperature below the normal, or the cooling of the air below its average condition, brings the capacity of the air for moisture down to and below the quantity it actually contains, resulting in supersaturation and producing rain. This is a rare occurrence at any season, and it almost never happens during the summer half year; and since the drop to this critical point is so great, it will still less frequently happen that falling temperatures will go far below it, and continue below it long, producing copious rain.

With a virtually constant quantity of contained moisture, the point at which a condition of saturation will be brought about by the lowering of temperature, and therefore the lowering of the capacity of the air for holding moisture, may best be defined in terms of temperature. Thus, at Yuma, in July, with the normal amount of moisture in the air, the highest temperature at which precipitation can begin, i. e., the normal "dew-point" temperature there, is 60.1 degrees; but the

normal temperature in July is 91.5 degrees. This is a much greater range (31.4) than is ordinarily compassed by temperature variation in that region. Hence the likelihood of any rain there is small, and of long-continued and heavy rain is practically nil; and this is so in spite of the fact that moisture sufficient for even a tropical precipitation is ever present in the atmosphere. On the other hand, at St. Paul, in July, the range between the normal and the dew-point temperature is only 13.9 degrees. Therefore, while at St. Paul the absolute humidity is less than at Yuma, nevertheless, what is called by meteorologists the relative humidity is much greater. The air in its normal condition at St. Paul is closer to saturation and less "dry," in the sense that by evaporation it takes up moisture at a slower rate. And as to precipitation, it is like a water vessel that is already nearly full and can therefore easily be made to run over.

Relative humidities may be illustrated in the same way. The condition of the air at St. Paul may be likened to a water barrel with open bung filled nearly to this opening. The bung in such case represents the saturation level, or the point (dew point) at which precipitation would begin if the water content (in nature the invisible vapor content) were to increase, the temperature remaining stationary at the midsummer normal. With the water content stationary, however, and the temperature varying, by rising and falling as it does in nature, we should have to imagine a vertical row of bungs which could be opened at will. The possible content of the vessel could thus be either increased or diminished; but evidently changes of the possible content would have no effect upon the actual content unless the level of the one were brought below that of the other. On the other hand, the condition at Yuma, comparatively, would have to be represented by a much more capacious cask with but a few inches of water in the bottom. Compared to what the cask would hold if filled to its open bung (representing the saturation level, or dew point, at the normal midsummer temperature), this amount of water would be small. It would be small relatively. In that sense the absolute humidity (the actual vapor content) of the air at Yuma is small. But this few inches of water in the large cask, if poured into the barrel, would be a relatively large amount there. At St. Paul the air can hold but a small amount of vapor because it is cool; at Yuma it can hold a large amount because it is hot. At Yuma it is charged far below its capacity; therefore the relative humidity there is small, evaporation continues rapid, and the air seems dry. But an equal quantity of vapor in the cool air at St. Paul, with its small holding capacity, would constitute a high relative humidity, evaporation would be slow, and the air sensibly moist or humid—even more so than it is in fact.

The ratio of this actual content to that required to produce saturation (and precipitation) is most conveniently expressed in the form of

a percentage. Thus, for example, at Yuma the normal relative humidity in July is given as 42.8. It is 42.8 per cent of saturation. At St. Paul it is 65.9.

A like comparison, with contrasts less violent, however, may be made between the barren High Plains and the great wheat-growing Northwest. In spite of the fact that the precipitation record shows a slightly greater fall at Amarillo than at St. Vincent, in spite of the fact, as the records show also, that the air normally carries more moisture in the southern Plains region than in the northern, the climate of the southern region is less than humid, or subhumid. That is to say, the relative humidity at Amarillo is less than at St. Vincent.

The Weather Bureau records at each station, among other climatic factors, take account (1) of the actual moisture content of the air (as vapor pressure); (2) of its dew point (as a temperature), and (3) of its normal temperature, but mainly in order that the liability of rainfall and the relative humidity may be determined. For, manifestly, it is a matter of small consequence what amount of moisture is actually in the air, unless at the same time it is known what amount is necessary to bring about the condition of supersaturation that alone could result in rain, and therefore how far the actual content falls short of this amount.[1]

Thus the normal relative humidity at Amarillo in July is 56.8, or 56.8 per cent of saturation; at St. Vincent it is 79.7. On a map which should show the normal relative humidity during the April-September

[1] "If water be introduced drop by drop into a vessel exhausted of air, such as the receiver of an air pump, the drops will be observed to disappear. They have evaporated or changed into the form of vapor. This evaporation will continue until a certain pressure of vapor is reached, after which any additional drops will remain liquid. The vessel is then said to contain saturated vapor. The pressure of saturation depends upon the temperature; the higher the temperature the higher the pressure of saturation. If, instead of a vacuum, the vessel had contained dry air, it would have evaporated precisely the same amount of water.

"Water vapor is always present in the air to some degree, although invisible until it condenses into minute particles of water, when it is seen as fog or cloud. Whatever the vapor pressure at any time, if it remains constant while the temperature is lowered, a point will be reached where condensation commences. This temperature is called the dew point. A further reduction of temperature causes a visible fog or deposit of dew. If the temperature be raised, the dew is again evaporated and disappears from view. Let the temperature rise still higher, and there is no moisture to supply the evaporation. The vapor is then said to be dry or superheated. If the number expressing the vapor pressure in the air at the time of an observation be divided by the number expressing the pressure of saturation due to the temperature at that time, the quotient obtained is a fractional part of saturation. This fraction is called relative humidity, saturation being 100 and absolutely dry air 0. Vapor pressure is expressed in terms of inches of mercury column which it can support. Absolute humidity, or the quantity of water contained in a given unit of air, is nearly proportional to the vapor pressure. It is stated in number of grains in weight contained in a cubic foot of air. The dew point is expressed in degrees Fahrenheit, as are other temperatures.

"Since relative humidity is a function of temperature, it does not constitute a means of comparison as to the quantities of moisture actually present in the air at different places and times. However, it is not the absolute humidity, but the percentage of saturation, which makes the extremes of temperature most annoying to animal life. Statements of relative humidity, therefore, in connection with those of temperature, give information concerning the comparative discomfort of life in different climates."—Arizona Weather, by Edward M. Boggs: Ariz. Agr. Exp. Sta., Bull. 20, 1896, pp. 5-6.

It should be added that hot air, which is at the same time "dry," and which is "comfortable" to animal life, since the evaporation which it causes keeps down bodily temperature, is, on the contrary, harmful to plant life, and to cultivated plants especially is seriously harmful, necessitating resort to irrigation in order to compensate for the loss sustained from excessive evaporation.

half year for the Great Plains as a whole it would appear that there is greater avidity for moisture over the southern Plains than over the northern. The air is more dry. Though precipitation is the same, owing to wider departures from the normal temperature, the air takes up soil moisture more rapidly.

SUNSHINE AND CLOUDINESS.

With a given amount of moisture already in the air, the rate of evaporation varies with the air temperature; but in direct sunshine the soil, and a layer of air in contact with it, may be raised to a temperature considerably higher than that of the air as a whole. Hence the loss of soil moisture will be the greatest, other things equal, in that region which has the largest number of hours of continuous sunshine.

The annual reports of the Weather Bureau give charts of the "average annual cloudiness," in parts, on a scale of 0 to 10, of the possible cloudiness. In the Plains region, it appears, the number of hours of sunshine, both for the year and for the summer half year, diminishes from south to north. At Dodge, upon the High Plains in western Kansas, and, in order northward, at North Platte, Nebraska, at Pierre, South Dakota, and at Bismarck, North Dakota, the records of annual cloudiness are averaged as follows:

Dodge	3.8
North Platte	4.4
Pierre	4.3
Bismarck	4.6

WIND MOVEMENT.

Wind contributes to the drying out of soil moisture by stirring the air layers, thus greatly accelerating the diffusion of the vaporized moisture through the air as a whole. In still air this diffusion takes place with comparative slowness. The rate of evaporation diminishes as saturation of the air is approached, and if the air remains undisturbed, upper dry layers can receive moisture only at the rate at which it can be transmitted through the lower moist layers. If there were no vertical component in the wind—i. e., if the air always moved in lines parallel to the ground surface—there would be no effect from it one way or the other upon evaporation. But wind contributes to the vapor loss of soil moisture, and of the moisture of foliage as well, by continually bringing relatively dry air into contact with it directly; and the stronger the wind the more vigorous and effective this action.

Another factor is change of temperature. A south wind, for example, may bring warm air, thus further increasing evaporation by raising the temperature; while either a north wind or a wind from off a mountain range may so lower the temperature that the algebraic sum of its two opposite effects may even amount to a reduction of evaporation.

Here again the High Plains are at a disadvantage compared with that large area of the Northwest having an equal or even slightly less precipitation. They have more wind in notable degree, and during the crop-growing season the direction of the wind is prevailingly from the south, while, as a rule, in the northern region a nearly reverse condition prevails.

The data are rather meager for statement of the normal wind conditions of the Great Plains as a whole. All of the requisite facts are noted only at stations of the first class, and among the large number of weather-record stations those of the first class, taking continuous note, automatically registered, of wind velocity, duration, and direction, are comparatively few. Of these, however, there is one upon the High Plains, at Dodge. Bismarck, in central North Dakota, on the same meridian as Dodge, and 9 degrees to the north, is another, and may be taken as fairly representative of the northern region of equal rainfall but greater effective humidity.

Following is an interesting presentation of the full records at Dodge and at Bismarck for 1897, as given in the annual report of the United States Weather Bureau for that year:

Velocity, duration, and direction of wind at Dodge, Kansas, in 1897.

1897.	Miles an hour.											
	1h a. m.	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	Noon.
January	9.2	10.2	10.0	10.7	11.3	11.8	11.1	11.1	11.8	12.6	13.4	13.6
February	9.1	8.8	8.1	8.5	8.4	8.6	8.9	9.0	9.3	9.5	10.2	10.2
March	12.7	11.5	10.4	9.9	9.6	9.8	10.3	10.2	11.0	12.8	14.2	14.0
April	11.6	11.6	11.6	11.3	10.0	10.1	10.9	11.6	14.0	15.8	16.5	16.6
May	9.2	8.2	7.7	7.3	7.1	6.4	6.8	6.9	9.0	10.6	12.4	13.0
June	12.1	10.7	9.5	9.4	9.1	8.6	8.2	8.8	10.9	12.6	14.0	14.2
July	11.4	10.7	10.2	8.9	7.6	6.8	6.9	7.3	9.8	12.5	14.3	15.3
August	7.3	6.3	5.9	6.0	6.3	6.7	5.9	5.9	7.4	9.1	10.1	10.2
September	10.4	9.4	8.3	7.0	7.5	6.8	5.6	6.1	6.8	10.5	13.2	14.5
October	10.5	10.7	11.0	10.4	10.0	9.0	8.2	7.7	8.6	11.1	13.5	14.4
November	8.8	8.3	9.0	8.9	8.7	8.3	8.2	8.4	8.0	10.0	12.4	12.8
December	9.0	9.3	9.1	8.8	8.9	9.2	9.4	8.8	9.2	10.2	12.3	13.6
Year	10.1	9.6	9.2	8.9	8.7	8.5	8.4	8.5	9.6	11.4	13.0	13.5

Velocity, duration, and direction of wind at Dodge, Kansas, in 1897—Continued.

1897.	Miles an hour.											
	1h p. m.	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	Mid-night.
January	13.5	13.5	12.8	11.8	10.6	9.3	8.2	8.0	8.4	9.1	9.0	8.7
February	10.9	11.7	11.2	11.5	11.1	10.4	8.4	6.8	7.7	7.9	7.8	7.9
March	14.5	15.2	15.3	16.4	16.1	15.8	15.5	13.7	12.9	13.0	14.0	13.5
April	15.8	15.5	15.1	14.8	14.3	13.8	13.3	12.4	11.0	11.6	11.2	11.1
May	13.8	13.8	13.9	14.8	14.9	15.2	14.9	13.5	10.1	9.5	9.9	9.7
June	14.3	15.6	16.8	17.5	17.8	18.0	18.1	16.0	13.2	13.3	13.4	13.2
July	15.1	15.5	16.1	16.2	16.7	16.0	16.1	14.8	12.2	10.5	11.2	11.1
August	10.6	10.8	10.8	11.1	10.8	10.9	10.5	9.5	7.7	7.2	7.2	7.6
September	15.3	15.8	15.7	15.8	15.8	15.3	14.9	12.2	10.8	10.0	10.0	9.8
October	15.2	15.0	15.3	15.2	15.0	15.0	12.8	10.2	10.2	10.2	10.4	10.5
November	13.6	14.3	14.3	13.8	13.4	12.1	9.4	8.7	9.1	9.0	9.0	9.4
December	14.8	14.7	15.8	14.4	14.5	12.0	9.3	8.3	8.2	7.7	7.3	7.4
Year	14.0	14.3	14.4	14.4	14.2	13.6	12.6	11.2	10.1	9.9	10.0	10.0

1897.	Miles an hour.		Duration, in hours.								
	Mean	Max. vel.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm.
January	10.8	36	121	79	7	43	140	92	71	182	9
February	9.2	36	105	124	17	106	68	76	51	117	5
March	13.0	51	96	106	32	148	124	95	42	95	6
April	13.0	50	127	61	21	119	117	62	24	179	10
May	10.8	40	45	112	40	199	233	78	6	15	16
June	13.1	67	65	70	13	118	351	73	10	18	2
July	12.2	41	53	52	14	82	376	81	9	68	9
August	8.4	32	48	110	30	145	245	89	39	33	5
September	11.1	40	48	45	8	118	448	28	12	2	11
October	11.7	39	84	72	3	73	302	74	64	69	3
November	10.3	37	110	41	5	65	193	118	42	137	9
December	10.5	48	115	61	16	65	77	89	97	219	5
Year	11.2	.....	1,017	933	206	1,281	2,674	955	467	1,134	93

Velocity, duration, and direction of wind at Bismarck, North Dakota, in 1897.

1897.	Miles an hour.											
	1h a. m.	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	Noon.
January	10.9	11.5	10.2	9.5	9.6	10.4	9.4	9.7	9.5	9.6	9.9	11.3
February	7.5	6.7	6.8	6.9	6.8	6.4	6.7	6.7	6.8	6.6	7.3	8.4
March	7.7	7.9	8.4	8.7	7.8	8.4	8.6	8.5	7.7	8.5	9.2	9.2
April	8.4	8.3	7.6	7.0	6.7	6.6	7.2	7.5	8.7	10.1	10.9	11.9
May	8.3	8.0	7.7	7.7	7.2	6.6	7.4	8.7	10.6	11.6	13.6	14.1
June	7.1	6.3	6.6	6.0	6.8	6.5	6.7	7.6	8.6	9.7	10.6	11.9
July	7.1	6.0	7.0	6.6	6.3	6.6	6.4	6.0	6.8	7.9	8.4	9.1
August	6.1	6.3	6.7	5.9	5.5	5.3	5.5	6.2	6.7	7.6	8.6	9.8
September	7.0	6.9	7.8	6.7	6.4	6.2	6.2	5.8	6.3	8.2	9.9	10.6
October	7.6	8.9	8.7	7.8	7.5	7.4	7.4	7.2	7.3	8.5	10.0	11.7
November	5.4	5.3	5.9	5.5	6.0	5.9	6.5	6.7	6.1	6.9	9.0	9.9
December	7.3	6.3	6.0	6.3	6.6	6.4	6.0	5.5	5.2	5.6	6.6	8.1
Year	7.5	7.4	7.4	7.0	6.9	6.9	7.0	7.2	7.5	8.4	9.5	10.5

1897.	Miles an hour.											
	1h p. m.	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	Mid-night.
January	12.4	12.2	13.8	13.5	12.5	11.8	10.5	9.9	9.4	9.5	9.4	10.4
February	9.8	10.8	11.2	11.4	10.8	10.5	9.4	8.8	7.9	8.1	7.7	7.6
March	10.1	10.2	10.3	10.5	10.8	10.8	9.9	8.6	7.6	8.0	8.1	7.8
April	13.1	14.2	15.6	15.6	15.9	15.0	14.5	12.8	10.5	9.5	8.9	8.7
May	15.4	15.6	15.8	16.0	15.4	14.6	14.8	13.9	10.7	8.7	7.9	8.4
June	12.3	12.8	13.5	12.9	12.6	12.4	11.3	10.3	9.5	7.8	7.6	7.0
July	10.3	10.8	11.3	11.3	11.1	10.7	10.8	10.7	9.2	7.7	7.9	7.8
August	10.4	11.2	11.1	11.6	11.1	10.6	9.9	9.5	8.5	7.8	7.0	6.4
September	12.0	12.9	13.5	14.0	14.0	13.0	12.1	9.7	7.9	7.6	7.9	7.3
October	13.4	13.7	14.1	14.2	14.3	12.5	10.5	8.2	7.1	7.4	8.2	7.2
November	11.4	12.7	12.9	12.9	12.3	10.5	8.5	7.4	7.1	6.5	6.3	5.3
December	9.5	9.8	10.3	10.9	10.5	8.2	6.6	7.9	7.8	7.9	7.7	7.5
Year	11.7	12.2	12.8	12.9	12.6	11.7	10.7	9.8	8.6	8.0	7.9	7.6

1897.	Miles an hour.		Duration, in hours.								
	Mean	Max. vel.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm.
January	10.7	47	31	37	46	80	24	20	18	403	85
February	8.2	48	31	129	91	63	20	31	33	184	90
March	8.9	35	97	96	109	107	26	16	40	194	59
April	10.6	47	148	42	60	128	47	32	64	169	30
May	11.2	36	113	61	95	148	102	23	14	183	5
June	9.3	41	97	51	94	187	70	40	25	135	21
July	8.5	35	97	52	90	165	76	35	38	147	44
August	8.1	48	69	91	114	146	79	11	34	173	27
September	9.2	34	22	36	134	165	65	29	27	210	32
October	9.6	39	72	31	58	137	66	33	46	280	21
November	8.0	36	92	56	90	68	43	33	44	253	41
December	7.5	40	26	63	53	112	52	21	66	305	46
Year	9.2	.....	895	745	1,034	1,506	670	324	449	2,636	501

The mean velocities, both for the year and for the crop-growing season alone, were notably greater at Dodge than at Bismarck. During the crop-growing season the hours of no wind, or of calm, at Dodge were 53; at Bismarck they were 159. And the hours of southerly winds—i. e., from either the south, southeast, or southwest—during the crop-growing season were, at Dodge 2,962, and at Bismarck 1,548. Of due south wind during this season, the hours were 1,770 and 439, respectively.

EVAPORATION.

In evaporation tests the record made is not of the actual evaporation loss. That could not well be determined. There is determined, rather, by experiment what the loss would be from free standing water, measured in inches of its lowered level. The actual loss from the soil is of course much less, but under like soil conditions it will everywhere bear the same ratio to the possible loss.

It appears that upon the Great Plains, outside of the distinctly humid belt, the average annual evaporation, under the most favorable condition of a free-water surface, largely exceeds the total annual precipitation. For example, the evaporation at Dodge is 54.6 inches and the precipitation only 20.4 inches; at Bismarck the ratio is 31.0 to 18.5. The precipitation is even a little less at Bismarck than at Dodge, but, as we have seen, the relative humidity there is greater, and consequently the rate of evaporation is slower. At St. Vincent the annual loss is 22.1 inches and the annual gain but 19.5 inches. So, even in the wheat-growing Northwest, evaporation exceeds precipitation, or would exceed it upon a lake surface. In the Lower Mississippi Valley, on the other hand, the reverse condition exists, and at New Orleans, where the precipitation is 60.3 inches, the evaporation is but 45.4 inches. Standing water there would gain by direct rainfall 14.9 inches in excess of the loss it would suffer from evaporation, but at St. Vincent it would lose, on the contrary, 2.6 inches, and at Bismarck 12.5 inches, while quite uniformly upon the High Plains this loss in excess of gain would be about 35 inches annually.

The High Plains may be taken as very nearly a unit area with respect to evaporation, while to the north of the Kansas-Nebraska boundary there is rapid decrease toward the northeast. Amarillo has an evaporation record of 55.4 inches; Dodge, 54.6 inches; while, in order northward, North Platte has a record of 41.3 inches; Bismarck, 31 inches, and St. Vincent, 22.1 inches. Yet at each of these points the precipitation, both annual and during the crop-growing season, is about the same, varying little from 20 inches.

SUMMARY OF DEFICIENCIES.

The climatic deficiencies of the High Plains are virtually summed up in this last statement of comparative losses from evaporation. The climate is essentially arid, or at least verges upon aridity, in that the air is dry and robs the soil of moisture excessively. Comparatively the climate of the northern Plains is humid, though in the same precipitation belt. It appears from the foregoing that humidity, in the general sense here used, is not a matter of rainfall, primarily, but of the condition of the air with respect to saturation. In this respect the High Plains are arid, and their rainfall or precipitation record, taken alone, therefore is misleading. A precipitation equal to that even of the famous Red River Valley of northwestern Minnesota does not suffice to render them humid.

The truer index of climate is the relative humidity of the air, or its percentage of saturation under average conditions, especially during the crop-growing season. Precipitation is to be regarded as resulting from a disturbance of the normal condition of the atmosphere—a disturbance, in the first place, of temperature, lowering it and thereby reducing the capacity of the air for holding moisture below that of its actual content. The High Plains are subject to a wider range of temperature than are the Plains of the Northwest, and the drops below the dew-point temperature are commonly greater, producing heavier precipitation; but at the same time they are more local in effect and of shorter duration, so that the total annual fall is not greater.

Summing up, then, in comparing the climate of the High Plains with that of the agricultural Northwest, it appears, as a matter of scientific record, that though the amount of precipitation in the two regions is the same, both annually and during the crop-growing season alone, yet the High Plains are at a more or less marked disadvantage, in that (1) summer rains there are violent and of brief duration, as a rule, rather than gentle and long continued, as they commonly are to the north; (2) secular variation from the normal precipitation works greater harm; (3) the normal summer temperature is notably greater; (4) the relative humidity is notably less; (5) there are more hours of sunshine; (6) there is more wind, which, during the summer, is prevailingly from the south, is warm, and therefore has a drying effect, whereas during the same season in the Northwest the prevailing winds are northerly; and, finally, (7) it is found that, following as an effect of the brief ponding rains, the high temperature, the low relative humidity, the almost uninterrupted sunshine, and the persistent high winds, evaporation is greater in a marked degree.

In short, despite the fact that their rainfall is fully equal to that which produces phenomenal wheat crops in the Northwest, the summer

climate upon the High Plains is dry. In a sense, precipitation may be regarded not as a normal factor but as an accident of climate, and, so regarding it, it may be said that the High Plains comparatively are arid, and require a heavier precipitation than those of the Northwest to produce like results.

Finally, the long records at Amarillo and at Dodge dispose in the negative of the question whether the climate of the Plains is undergoing change for the better, or, indeed, any change whatever of a permanent character. Daily observation, extended over a quarter of a century, plainly exhibits stability, in the long run, while the oscillations above and below the mean, in groups of years, are to be regarded as operating on the whole as a disadvantage, working more harm in dry years than can be compensated for in years of plenty.

CHAPTER IV.

IRRIGATION NECESSARY TO AGRICULTURE.

So long as any considerable body of land in the humid zone of the Plains remained unoccupied, no experiment in agriculture was attempted to the westward in the "short-grass" country. The eastern limits of the Great American Desert had been pushed back so far as to include in the agricultural area the humid belt of undulating prairie, carpeted with long grasses and with trees bordering its numerous streams; but the flat upland stretches of the High Plains, streamless as well as treeless, appeared still unmistakably to have the character of an irreclaimable desert.

Distinction had been drawn between prairies and plains proper. The desert was recognized as beginning only where the prairies left off, extending thence to the mountains. Another distinction was now made in further subdivision. It was noted that the western half of the so-called arid plains remaining was considerably eroded and had flat areas preserved only in small isolated patches, while the eastern half, with its closely knit sod as distinguished from bunch grass growing in tufts, was unscarred and flat, excepting where mountain streams had cut valleys across it in north-south order at wide intervals. Consequently with the pioneer cattleman of the extreme western belt it came to be said that to journey eastward was to go "out on the Plains," upon seemingly interminable stretches of flat land. From his side the Plains proper lay to the eastward; beyond extended the undulating prairies of the humid region.

The western belt of dry-climate erosion descends toward this central uneroded belt, and the eastern belt of humid-climate erosion drops away from it; but erosion on the east is being extended westward by head-stream sapping on the part of a multitude of small spring streams draining off the upland ground water, and there has resulted here a fairly definite and nearly continuous boundary having the character of an eastward-facing escarpment, as shown on Pls. CXIII and CXVIII and in figs. 300 and 307. From the prairie side the intermediate region therefore stands in light relief as uplands, and it is from this side that it has received the appellation of the High Plains. But aside from distinctions by topographic difference, it came to be recognized also that the central flats differed from the extreme western belt on the one hand in the character of their rainfall mainly, and

from the extreme eastern belt, on the other, mainly in the volume of it. By the western stockmen they were designated the "rain belt," by which was meant that desert conditions therein were in a measure mitigated merely.

With the final complete occupation of the eastern prairies, however, and the demonstration there of a fertility and productiveness not previously suspected, the term "rain belt," applied to this lightly watered fringe of the desert, came to be in large part responsible for an attempt which immediately followed to reclaim still another zone from the Arid Lands. The attempt was made by cultivation and planting alone, without artificial watering. It was an experiment in agriculture on a vast scale, conducted systematically and with great energy, though in ignorance or disregard of the fairly abundant data, indicating desert conditions, which up to that time the Weather Bureau had collected. Though persisted in for several years with great determination, it nevertheless ended in total failure. Directly and indirectly the money loss involved was many millions of dollars. Full measure of the harm resulting should take account also of the immigration into other regions of a class of people broken in spirit as well as in fortune.

The movement of settlers onto the High Plains was an inroad. The only population there at the time consisted of a few stockmen, making common use of the public range. The newcomers were farmers and town builders. Elsewhere in the Arid Region stockmen, holding the public lands as common range, had had to contend with immigrating farmers, but always in small numbers and with the advantage on the stockman's side that, having been first on the ground, he already held the desirable ranch sites. The farmer's aim heretofore had been agriculture by irrigation along the stream bottoms; at most the stockman had been merely inconvenienced; the interstream areas in any case were left in his possession undisturbed. But in this instance irrigation was not in contemplation; the interstream areas, not the valleys, were invaded, and in some parts of the High Plains, notably in western Kansas, the stockmen were completely dispossessed.

The movement was an inroad in the sense also that it began abruptly, and rapidly brought in a large population. The humid zone merges into the subhumid by insensible climatic gradations; but, as we have seen, the High Plains, as approached from the eastward, are distinctive topographically. A strip immediately adjacent on the east is minutely cut up by the multiple spring-creek headwaters of eastward-flowing streams originating there, so that transition is from a region of intense degradation to flat uplands of seemingly boundless extension. This eroded strip, furthermore, is one of headwater capture from the High Plains, lying within the subhumid belt to which the High Plains themselves belong. The undulating prairies, of humid climate, begin

well to the eastward, so that in climate also there is perceptible change, as between prairie and uplands, proportioned to the breadth of this intervening belt captured from the latter. There is equally marked difference in soil, for that of the upland flats is unstirred by surface run-off and is the product merely of decay in place.

Responding, then, to both climatic and soil differences, the grass covering of the High Plains differs also, and in marked degree, from that of the eastern prairies. Though of a lawn-like continuity, the growth is too short for cutting; but the depth and firmness of its sod and its nutritious quality, retained the year around, were taken as demonstration at least of fertility of soil. The universal green with which each spring it carpeted the High Plains came to be regarded as a sure promise that planting to wheat would at once result in another notable extension of the agricultural area.

The gradual westward progress of emigration had received a definite check at the farther limit of the prairies; between the prairies and the High Plains the minutely eroded headwater strip intervened. Emigration had halted until the prairie lands of all grades had first been fully taken up. In proportion, then, as the movement had for a time been stayed, it now proceeded quickly and in larger volume.

THE AGRICULTURAL EXPERIMENT.

From records of the Weather Bureau, presented in the last chapter, it appears that while the climate of the High Plains is in the long run subhumid, it varies greatly nevertheless through groups of years from fairly humid to arid; and that, furthermore, since rise above the mean has to be of notable amount before humid conditions are attained, the periods favorable for merely fair yields of humid-climate crops are comparatively of brief duration.

Though immigration had an abrupt beginning and continued rapidly, it did not take on the proportions and assume the character of a "boom" until after several years. That is, the movement was not from the outset advertised and promoted. It was prolonged and swelled by these means on the part of railroad companies and town builders; but the explanation of its inception is to be sought rather in the fact of the prevalence of exceptionally heavy rains during the years (1883–1885) just preceding.

Sherman County, in western Kansas, may be taken as fairly representative of the central area of the High Plains into which immigration was heaviest and in which the "boom" was most actively conducted. Of flat uplands this county has nearly 1,000 square miles. The total upland area of the High Plains belt, closely approximating the total cultivated area of the State of Iowa in the census year 1890, is about 40,000 square miles. In 1885 the population of Sherman County was 1 person to 10 square miles; the next year it was 3 to 1

A. THE CARPET OF GRASS

B CLEAN SWEEP OF THE PRAIRIE FIRE

square mile. In 1889, three years later, it had risen to nearly 6. During the next four years, up to 1893, it increased but little; and by 1896 it had dropped to 4. The height of the "boom," as well as its heaviest penalties and the end of it, was in 1893. During the decade 1885 to 1896 the possibilities of irrigation in the valleys from the larger streams were barely considered. Settlement and all attempts at farming were confined to the uplands. Expectation had been that it would be possible to achieve upon these smoother and more easily tillable plains a reclamation similar to that which had been so easily accomplished in the State of Iowa, for example, and the first attempts in this direction had been abundantly encouraging. The yield, not only of wheat, but of every variety of crop experimented with, exceeded expectations. An idea of the character of these crops may be had from photographs *A* and *B* of Pl. CXXVII, though these photographs were actually taken at a later date in a similar season of plenty upon the uplands farther south.

With such demonstration, under slightly improved climatic conditions, of the possibilities residing in these vast unbroken stretches of fertile land, it is not to be wondered at that in the ardent desire to turn

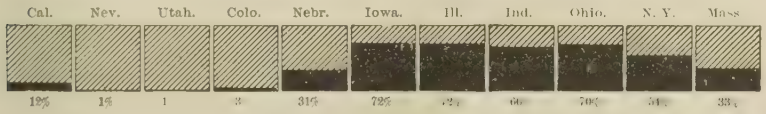


FIG. 309.—Comparison of cultivable and cultivated areas in belt of States across United States.

them to account originated the belief that extensive and persistent cultivation alone, by regulating evaporation, would bring them an equable and humid climate. That the inducement to make the attempt was great must be conceded when it is recognized that nearly the whole of the 40,000 square miles is susceptible of easy cultivation. From the census records of 1890 it appears that the cultivated area in Massachusetts in that year was but 33 per cent of the whole. While this is not the measure of the cultivable area in that State, it is nevertheless true that the area in Massachusetts which is as easily cultivable as nearly the total area of the High Plains is much less than 33 per cent.

Fig. 309 gives the ratios of cultivable areas to areas cultivated, in 1890, in a belt of States from Massachusetts to California. The cultivated area in New York is 54 per cent; in the North Central States it ranges from 66 to 72 per cent; in Colorado it is 33 per cent; in Utah and Nevada, 1 per cent, and in California 12 per cent. Even the reclaimed area in the prairie State of Iowa, almost precisely equal to the upland area of the High Plains belt, is notably inferior in ease of cultivation to the latter. The cultivated area in California is less than half the area of the High Plains, and is furthermore handicapped, in the main, by necessity for artificial watering.

The maximum of cultivation upon the High Plains was reached in 1893. Fig. 310 presents a relative statement of the total areas and the areas cultivated in that year in the North Central States and upon the High Plains, respectively. Considering the extraordinary ease of cultivation there, a comparatively small result has been achieved in the latter region.

Much is heard of the high productiveness of the so-called Arid Lands, when by irrigation they are brought under cultivation, and of

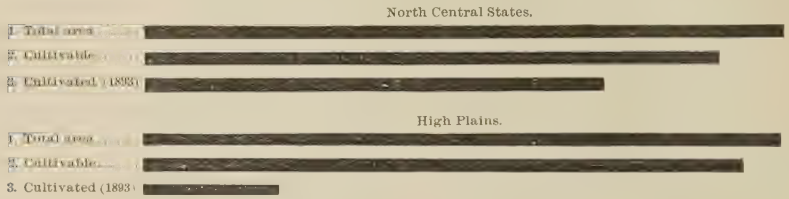


FIG. 310.—Comparison of cultivable areas and areas cultivated in 1893 in North Central States and on High Plains, respectively.

the importance and value of the results already achieved in their reclamation. In the main these statements are not exaggerated. But ideas which are greatly exaggerated nevertheless prevail as to the proportion of the areas reclaimable and actually reclaimed. The total area of the Arid Region may be taken, in round numbers, to be 800 million acres. Of this total it is estimated that not quite one-half is cultivable—that is, if irrigation were not necessary, so much could be farmed with profit—but it is estimated also that, from all sources,

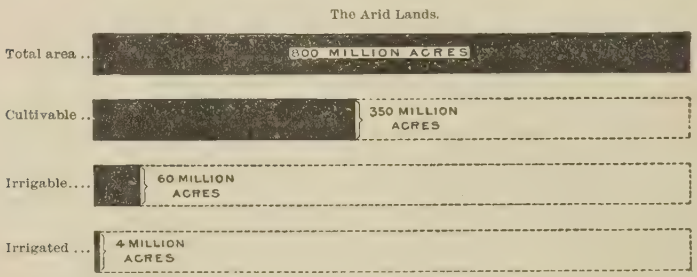
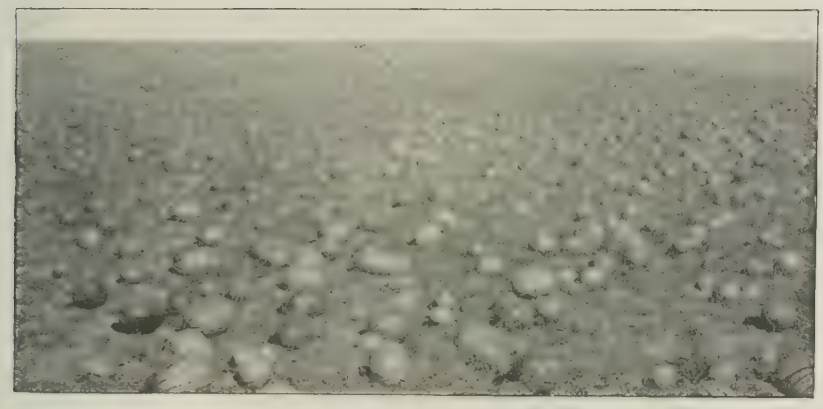


FIG. 311.—Comparison of cultivable, irrigable, and irrigated areas of the Arid Lands.

there is water available for the irrigation of not more than 60 million acres. In other words, only 7 per cent of the whole is reclaimable—a proportion notably less than that in rock-encumbered Massachusetts. Finally, the actually irrigated area, of which we hear so much, is but 4 million acres, or one-half of 1 per cent of the whole.

As a zone mistakenly regarded as arid, and which was now to be reclaimed from that apparent condition merely by persistent cultivation without irrigation, the High Plains appeared to be exceptionally

A A WET-YEAR CROP.



B. A WET-YEAR CROP.

C. PLOWING BY STEAM.

favored. They had no mountainous tracts with bordering wash plains of coarse débris, bare of soil, to be deducted from the total. There was presented, on the contrary, a dead level of nearly uniform fertility, having the appearance of farming land of the choicest quality. But the hope of reclamation had no scientific basis. No consideration, for example, was given the all-important question whether, quantitatively, the possible saving in evaporation losses would be of practical account. That was left for determination by actual trial. The hope had had its origin rather in the pressing need for another ample expansion of the agricultural area, and in the fact that the High Plains seemed to meet requirements ideally, excepting only in one particular. The plan proposed for remedy of this single defect was not of a kind calculated to discourage effort. It was merely to proceed with the occupation as rapidly and on as large a scale as possible, leaving that task to the

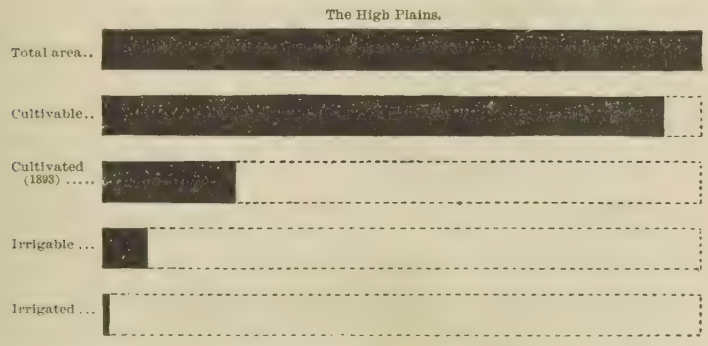


FIG. 312.—Comparison of cultivable, cultivated (1893), irrigable, and irrigated areas of High Plains.

operation of natural agencies under the new conditions. It was not contemplated that there would be need for artificial aids, such as supplemental watering—i. e., irrigation.

The costly undertaking was not entered upon as an experiment, however. From the outset its success was taken to be assured, and the immigrant as a rule invested in it the whole of his possessions. As a rule, also, he mortgaged his lands in following years.

If the multiplied indications of virtual aridity presented by the Weather Bureau records during a quarter of a century could not be accepted as conclusive, they now at least may be so regarded in the light of this added evidence from a practical test involving the continuous cultivation for more than a decade of some thousands of square miles. Including its valley areas, in which there has been some progress in reclamation by irrigation, the condition of the High Plains belt at the present time is comparable to that of the Arid Lands as a whole. Its cultivable, or more strictly speaking its tillable, area is relatively much greater; but its irrigable area is small, while that actually irrigated is comparatively minute.

In more detailed statement of what was actually accomplished by this experiment in agriculture, fig. 313 is presented, giving the areas planted each year for the twelve years, 1885–1896, upon the flat uplands in Sherman County, western Kansas. Immigration was heavier into southwestern Kansas; on the other hand, it was lighter farther south. It will be seen that the area planted had slow increase from 1885 to 1888; that in the year 1889 it was trebled, though in the following year it fell back halfway, and that it then rapidly increased for three

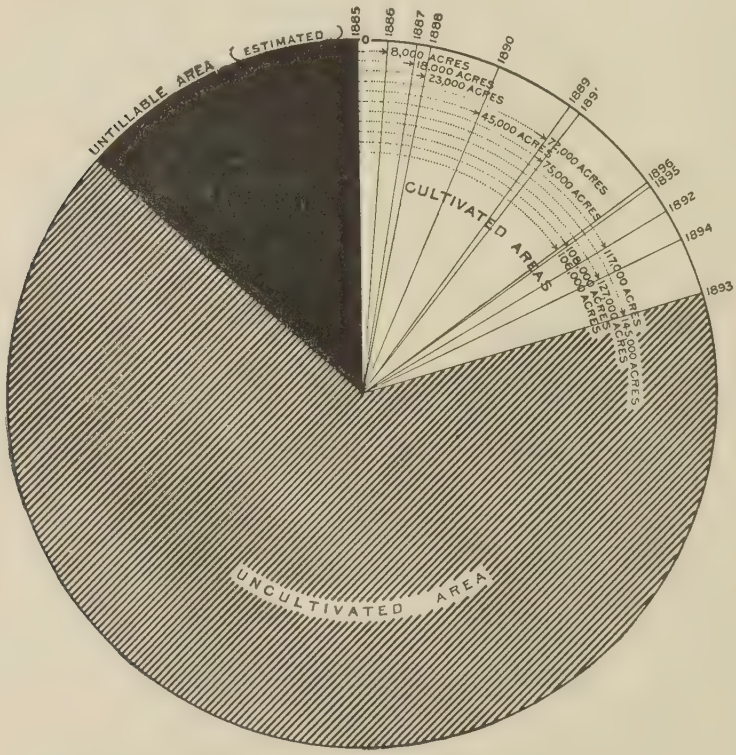


FIG. 313.—Comparison of cultivable area and area cultivated each year for twelve years in Sherman County, Kansas.

years, reaching the maximum in 1893. But the years of heaviest planting as a rule coincided with the years of light rainfall, and were those of heaviest loss. For example, in 1888 there was a heavy fall and abundant harvests from the small area planted. The trebled area of cultivation in 1889 followed in consequence of this encouraging showing; but the rainfall in 1889, on the other hand, was light, and the resulting loss was large in proportion as the expense of planting had been heavy. The following year there was some discourage-

ment and diminished planting. However, the small profit, due to a small rise here in the inches of precipitation, led to the belief that cultivation was after all beginning to tell, and the "boom" may be said to have started. Immigration and planting rapidly increased. In 1891 there was an exceptionally heavy fall, and as this was coincident with liberal planting there was a large profit. The area planted the next year was increased by fully 50 per cent; but the climatic conditions that year were not so favorable, and there followed marked decline in profits. Little discouragement resulted, however, and 1893 showed another notable increase in the area under cultivation. But 1893 was a year again of desert dryness, and there was complete loss. Drought continued for the next two years, to 1896, inclusive, making four consecutive seasons of no return, yet the acreage cultivated diminished but slowly. The failure of 1896, however, resulted in total collapse and heavy emigration, and though 1898 brought again a humid maximum the abundant rains of that year fell mainly upon abandoned lands and the scanty, unharvested crops of a previous season.

Briefly summarizing, we have: (1) a one-year period (1888) of humid-climate conditions, which gave origin to the agricultural experiment; (2) a one-year period (1889) of arid conditions, yet of heavy planting and therefore of total loss; (3) a one-year period (1890) of light planting, but of fair precipitation and moderate profits; (4) a two-year period (1891–1892) of heavy planting coinciding with heavy precipitation, and therefore a period of large profits; (5) a four-year period (1893–1896) of continuous heavy planting, but with the calamitous accompaniment of continuous drought, and, finally (6), in 1898, a return to humid conditions, though after all effort had come to an end.

Especially instructive are the results achieved during the six years from 1891 to 1896, considered in the two groups, first, of two good years (1891–1892), in which heavy planting coincided with heavy precipitation, and, second, of four following years of unbroken drought (1893–1896), in which planting even increased until brought to an end by the exhaustion of working capital.

DROUGHT-RESISTING CROPS.

Among the several cereals wheat continued the favorite, but at the same time there was active experimentation on a small scale with sorghum and other varieties of cane, with a view to their use as supplemental feed for sheep and cattle. Energy continued to be devoted mainly to farming for export; stock raising and the growing of forage for stock were altogether incidental. Nevertheless, the results of the experiments with sorghum and other dry-climate canes are the only ones which contain anything of promise for the future of the High Plains.

In fig. 314 we have the relative mean values of the acre yields of

wheat in western and eastern Kansas, first, for the humid two-year period; second, for the arid four-year period, and, finally, for the entire period of the experiment. The four-year drought was felt in eastern Kansas as well, but there was some profit there over the cost of production. During the two wet years, on the other hand, the

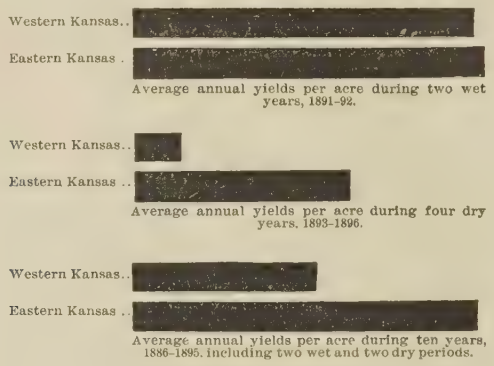

Western Kansas..
Eastern Kansas .
Average annual yields per acre during two wet years, 1891-92.
Western Kansas..
Eastern Kansas ..
Average annual yields per acre during four dry years, 1893-1896.
Western Kansas..
Eastern Kansas ..
Average annual yields per acre during ten years, 1886-1895, including two wet and two dry periods.

FIG. 314.—Comparison of acre yields of wheat in western and eastern Kansas.

High Plains made very nearly as good a showing as the East. But, averaged for the whole period, their yield fell short of a profit.

If now, taking western Kansas alone, the results with wheat be compared with those with sorghum, as in fig. 315, there is apparent for the latter a marked advantage, as well as a profit in some measure, under all conditions. Other crops of the humid-climate varieties, which were found to do well during wet years, were corn, rye, barley, oats, and

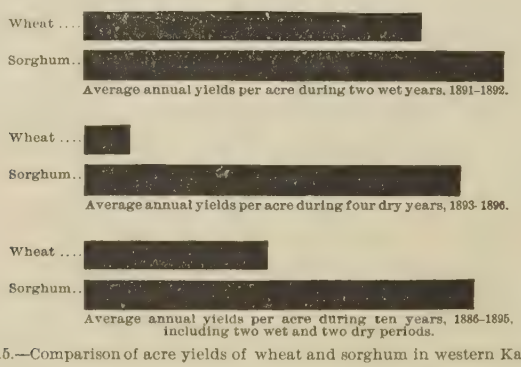

Wheat ....
Sorghum..
Average annual yields per acre during two wet years, 1891-1892.
Wheat ....
Sorghum..
Average annual yields per acre during four dry years, 1893-1896.
Wheat ....
Sorghum..
Average annual yields per acre during ten years, 1886-1895, including two wet and two dry periods.

FIG. 315.—Comparison of acre yields of wheat and sorghum in western Kansas.

potatoes. Grouping these as humid-climate crops, for comparison with results from sorghum, etc., it will be found from the values of the acre yields of the former that on the average they were notably below the acre yields of the latter. The numbers of cattle and sheep had been considerably increased also, and sorghum acquired its superior value

A. ABANDONED SCHOOLHOUSE.

B. ABANDONED TOWN.

largely from the fact that in dry seasons it was needed for forage and found its market on the ground. Its high value, as here given, was in a measure fictitious, in the sense that it would not have been nearly so great if its product had been large—that is, if the total acreage had been devoted to its growth. But relatively it was a successful crop, none the less.

The comparative areas devoted to these humid-climate and dry-climate

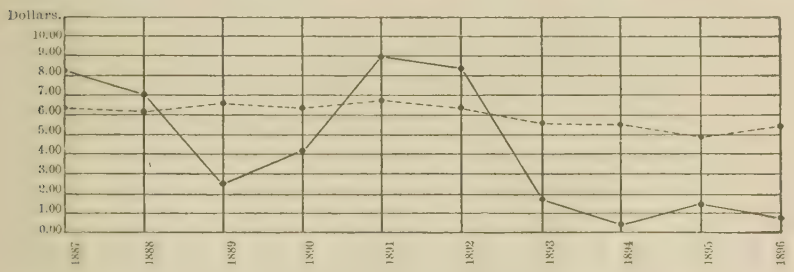


FIG. 316.—Comparison of values of acre yields of humid-climate crops (solid line) and drought-resisting crops (broken line) in western Kansas.

crops, respectively, as averaged from the reports of several counties in western Kansas, are graphically exhibited in fig. 316. It will be seen that the area devoted to cane (chiefly sorghum) had slight increase during the 1887–1896 decade and was comparatively small, while that devoted to the cereals (chiefly wheat) had great increase and large fluctuations. But from fig. 317, giving the values of the acre yields of

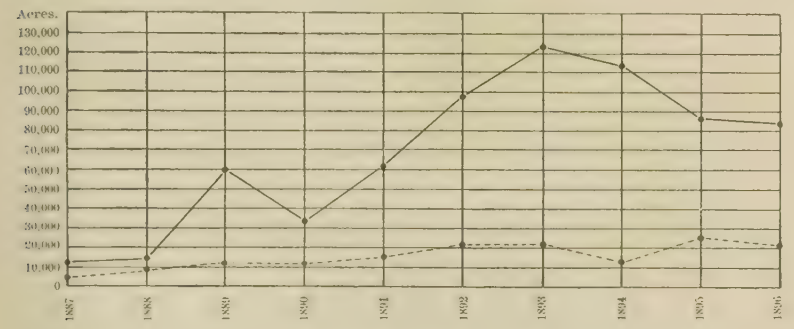


FIG. 317.—Comparison of areas planted to humid-climate crops (solid line) and to drought-resisting crops (broken line) in western Kansas.

humid-climate crops and dry-climate crops, it appears that the latter retained a nearly uniform and high value. Though the yield of sorghum in tons per acre diminished somewhat during dry periods, its value per ton increased, and there is therefore shown a slight tendency toward a maximum, coinciding with each minimum yield of wheat.

The lesson of the crops, which seems to be conspicuous here, is that it pays on these subhumid plains to raise cane forage if there be stock

at the same time to which to feed it, and that even in the periods of drought the drought-resisting crops will produce a yield of some value. In short, it is not practicable upon the High Plains to farm for export. Without supplemental watering the average yield of the cereals and of farm products in general will fall below the cost of production.

THE VISIBLE EVIDENCES OF FAILURE.

An idea of the magnitude of the scale on which the attempt to farm the High Plains was made, especially in western Kansas, as well as of the great aggregate losses that must have resulted from the utter failure of this attempt, is strikingly to be had from the frequent spectacle of abandoned towns systematically spaced apart upon the flat uplands in anticipation of a dense but uniform farming population, for which they were to have been points of supply. In disregard of the possibility of failure, the first step in the occupation of the country was the building of these well-appointed towns. Their sites now, as a rule, are marked merely by parallel rows of cellar excavations, with iron hydrants perhaps at street crossings, and by occasional isolated public buildings of brick or stone from which all doors and windows and interior furnishings have been removed. Frame structures of every description have been carried off bodily to distant valleys for use there as ranch buildings. Outside the towns sod was employed almost universally in the construction of farmhouses. Of these even the roof beams have been removed, leaving only the plastered sod walls remaining as rapidly crumbling ruins. The rectangular subdivision system of the Land Office is indicated almost universally by plowed roadways, blocking out square-mile sections, within which the old plowed fields, amounting in the total to millions of acres, are slowly returning to grass, while occasional leaning fence posts, with dangling strands of barbed wire, mark the former lines of many thousand miles of fencing.

The great body of emigrants have either returned to the East or have drifted farther west. A small percentage has scattered along the bottom lands of the larger valleys. On the vast upland flats, however, an occasional settler remains, and he has become a "stock farmer." His location is always first to be discovered by means of a windmill wheel turning above the horizon. A field of sorghum surrounds the house, and a "bunch" of cattle range without its rectangular fenced inclosure to a radius not too great for easy return to the pumping trough. The stock farmer is merely "holding on," waiting for a change of climate. It is his bunch of cattle, making use of the natural grass crop, which enables him to do so. But as a rule his hope and his ambition are, after the temporary unfavorable conditions—as he regards them—shall have passed, to return to the growing of wheat for export.

A. SOD-HOUSE RUINS.

B CISTERN NEAR SOD-HOUSE RUINS.

SOIL STORAGE AN APPRECIABLE AID TO FORAGE CROPS ONLY.

Scientific cultivation takes account of the fact that it is practicable to retain in the soil a larger portion of the moisture which it absorbs immediately after rain than is retained there under ordinary methods of tillage. Rainfall is disposed of by natural processes in three ways: A portion sinks into the ground; another portion runs off; a third is evaporated. So far as immediate plant use is concerned, the run-off and evaporation losses are complete.

Of the absorbed portion utilization is only partial, however. This ground moisture does not long remain in the soil zone, and for utilization of it plants require time. There is a tendency for it all to continue downward and eventually come to rest as a contribution to the ground water, below the "water-plane" level of which the ground pores, by long repetition of this process, have become saturated. If the soil and subsoil be dry, this downward tendency will for a time be aided by the pull of capillarity. By capillary tension water is drawn from moist ground into dry, whatever the direction, and at first the strongest pull will be downward, aiding gravity. After the passage of a surplus the effect of capillarity, however, is to slow descent.

The action of evaporation is not wholly superficial; it is penetrating as well. It will be felt in the partially air-filled pores, at a slowing rate, immediately following the first downward passage of water in large volume; and with drying near the surface capillary tension overtakes and vigorously returns some portion of this water toward the surface. In this return, growing plants are nourished, but in part also there is contribution to the earlier complete loss by evaporation.

In soil storage, scientific cultivation, by packing the ground at a slight depth, creating a floor, and by formation of a "dust cover" above, accomplishes a detention within the zone of growth of that portion of the rainfall which had not at once escaped from the surface by run-off and by evaporation. It diminishes both downward and upward escape.

This detention is partial and imperfect. The resulting gain can be but slight. It will be of importance where only a small addition to the normal supply is required. But the additional supply needed upon the High Plains for wheat is large.

Soil storage has telling effect during periods of minimum rainfall in humid lands. In a region where drought is the normal condition it should amount to an appreciable aid in the growth of dry-climate crops, such as the sorghums, if economically practicable; but it could not sustain wheat through a normal season upon the High Plains.

CHAPTER V.

IMPOSSIBILITY OF GENERAL IRRIGATION.

The settlers upon the High Plains were from the East and without experience in irrigation. They were not unacquainted with the large results which had been attained by artificial watering in the Arid Region, but the means there employed involved the grafting upon simple farming of unfamiliar engineering practices for which they had no inclination. Furthermore, the upland areas of the High Plains belt were so far removed from streams that their watering in this manner appeared obviously to be a vast undertaking. Though projects for diversion of the Arkansas, the Platte, and even the Upper Missouri to this central region had early been broached, they had received little attention, and upon failure of his original programme the Eastern emigrant abandoned the field as abruptly as he had entered it.

THE MOUNTAIN STREAMS OF INSUFFICIENT VOLUME.

Meanwhile, however, Western irrigators had begun canal and ditch development along the valley of the Arkansas.

EXPERIMENT WITH THE ARKANSAS.

The town of Garden, in western Kansas, had its inception as an irrigation community. Here extensive diversion works, taking water from the Arkansas River, accomplished the reclamation not only of a breadth of river bottom, but of a considerable acreage also upon the uplands. There was no storage of the out-of-season flow, nor any attempt to utilize flood flow; but the possibilities of the normal run of the river at this point were realized to the full. The upland area thereby reclaimed, however, though sufficient to give origin to a town of some importance, amounted to an insignificant fraction of the whole. It could not, for example, without exaggeration in size be clearly shown upon the general map of the High Plains (Pl. CXIII). A like demonstration of insufficiency of the easily manageable supply during the crop-growing season was made along the Platte in central Nebraska.

The results actually attained were in themselves abundantly worth while, but as a measure of the possibilities of general reclamation of the High Plains they showed that the mountain streams were wholly unequal to the task, unless recourse might be had to storage.

MEAGER POSSIBILITIES FROM STORAGE.

Complete storage, not only of the out-of-season flow, but of the very heavy flood flows of all seasons as well, would manifestly call for engineering constructions of great size and cost. It was generally believed, in the absence of detailed information bearing upon the volume of water which might thus be obtainable, that the volume would be ample. It may easily be made apparent, however, that any such estimate is greatly mistaken. Not even with the fullest storage and practically complete utilization could the mountain streams be made to avail for irrigation of any considerable portion of the High Plains.

Storage on any great scale, in the sand-wash beds of the Arkansas and the Platte, is out of the question. As we have seen, the arid belt to the west of the High Plains, originally overspread and built up by streams from the mountains at a rate more than sufficient to offset any erosive work of its local precipitation, now finds the mountain streams, confined in valleys across it, cutting down to a new grade, leaving the intervalley areas to the effects of desert erosion unobscured. The arid belt is without the sod covering which in the next climatic zone to the eastward, also above grade, prevents concentration into lines of drainage and the beginnings of degradation. In crossing it, therefore, the mountain streams receive a notable contribution to their burden of silt. Flood storage upon the Plains, even if practicable, would in consequence be uneconomical, in that the life of reservoirs would be too short. They would too soon become silted up. But such storage in the absence of natural dam and reservoir sites along the trunk-stream valleys would not be practicable. This will be the opinion of engineers. It will be reached from a point of view which those who are not engaged in large undertakings of the sort do not often take. Storage should be in the mountains and distributed among the tributaries rather than wholly on the main trunk of a stream in the foothills. Then, in order to minimize the inevitable large losses of a desert stream by ground absorption and by evaporation, diversion and application in irrigation should take place as close to the mountain foot as practicable.

For example, to utilize the Arkansas in the arid belt would result in the reclamation there of a larger area than upon the High Plains, in proportion as the loss in getting it to irrigable lands in the former case would be less; and the difference would be marked. At least these mountain streams owe a first duty to the lands they traverse first; but since lands close at hand are watered at a smaller cost in evaporation and seepage losses, they should first be served to as large an extent as possible, if the result desired be the largest possible measure of reclamation.

As to just how large a measure of reclamation is practicable, upon examination it is at once apparent that within the arid belt alone there

are cultivable and fertile lands, accessible by canals and ditches, in larger amount than could be covered by the total annual flow of the mountain streams, floods included. In other words, with the fullest and at the same time most economical utilization of the run-off from the mountains, it would be found that the supply would fall short of demands before the High Plains could be reached. That it must so fail is at once apparent when it is noted how inconsiderable is the catchment area within the mountains which has drainage eastward as contrasted with the vast area of the Plains over which it is proposed to distribute mountain water, and when, furthermore, it is seen that the mean annual precipitation in the mountains is far from heavy, is in fact light as compared with that, for instance, of northern Washington. The important fact to be recognized here is that the streams which traverse the Plains from the Rocky Mountains—their pulsations in floods included—are not strong-flowing rivers, such for example as the Nile, or the rivers of India which issue from the Himalayas. To parallel the case of India and the Himalayas, the Plains region should slope the other way and the Appalachian humid region to the east should drain, not to one side into the Gulf, but westward across it. As the case actually stands, there is not water enough from the Rocky Mountains completely to utilize even the extreme western and arid subdivision of the Great Plains.

The High Plains present a larger expanse of accessible and cultivable lands than this arid belt. To reach them across the latter would involve so much loss from seepage and evaporation that the area reclaimed would be much smaller than could be reclaimed close to the mountains, and an area in proportion to the whole insignificant. But the claims of the arid belt could not be thus wholly disregarded. Hence, even with complete storage and under an equitable arrangement, the High Plains could expect to receive no appreciable benefit. It is very doubtful, however, whether complete storage will ever be found to be economically practicable. It may be accepted as certain that it will not in any case be undertaken for the reclamation of lands at a distance when lands are to be found close at hand which are reclaimable at less cost.

The experiment of upland irrigation from the Arkansas River near Garden was at first strikingly successful. Three long canals and many miles of distributary ditches were constructed, and although the upland area thus brought under cultivation was relatively minute the large profits resulting operated to hasten the discouragement of those who up to this time had been depending upon the meager rainfall alone. It failed in turn, however, because of increasing demands on the river in the arid belt to the westward, in Colorado, resulting finally in the drawing off of its total run during the growing season. It soon came to be facetiously remarked of this elaborate and well-

devised irrigation system that it constituted the finest display of dry ditches in the Arid Lands.

The out-of-season flow of the Arkansas at Garden still goes by, but large undertakings already on foot looking to storage in the mountains foreshadow the eventual complete disappearance of the river in western Kansas, except as it may from time to time be briefly rejuvenated by floods too large to be manageable.

THE CANADIAN AND THE PECOS.

From examination of the map (Pl. CXIII) it may at first sight appear that the Canadian and the Pecos rivers offer some hope of reclamation for the Staked Plains plateau, since the western arid belt seems not to be represented there; but in the case of those streams, as in that of the Arkansas and the Platte, the same objection applies, namely, that they are not great rivers. The Pecos Valley west of the Staked Plains could make full use of all of its waters; and while the valley of the Canadian is not well supplied with bottom lands within the High Plains belt, it nevertheless broadens just without, to the eastward, and the stream may readily be utilized there, before the humid zone is reached, to as great extent as impounding and control of its flow may render possible. In the case of either stream the point of its diversion to the upland area, on account of the general high elevation there, would of necessity be well toward its headwaters. The Pecos is mainly fed along the western side of its valley below this point. Its volume where it could be taken out is so small it is not unlikely that it would not even survive the losses incident to diversion and long canal transportation. Furthermore, the initial cost of impounding and of diversion works, together with the cost of maintenance, would be prohibitive, in view of the small result that under any possibility could be achieved. The latter considerations apply equally to the Canadian.

Probably the early experience in upland irrigation, by diversion of the Arkansas at Garden, where the problems were of the simplest character, is the last that will be made.

LOCAL STORM-WATER STORAGE.

The High Plains have been described as flat, as, in fact, characteristically presenting to the eye the appearance of a dead level. This impression is strikingly conveyed in Pls. CXIV and CXXVI (pp. 610 and 682). The old Tertiary plain, of which the central uplands are remnants merely, has been described as flat originally (with imperceptible inclination eastward), and as having since Tertiary time retained that character within the subhumid zone, because protected there by its sod covering against the beginnings of erosion

and the development of surface drainage. It has been pointed out also that since the cessation of plain building and the initiation of destructive processes the only effective erosion has been performed by traversing mountain streams cutting transverse valleys, and by streams of the humid region to the eastward carrying back the eastern boundary as an escarpment by headwater sapping, fed and aided in this work by escape of the upland ground water at the escarpment foot. In the main this is an accurate statement. There are here and there lines of depression along which drainage is faintly traceable, but it is doubtful whether any of them have had their origin in the erosive work of surface run-off, and it is only rarely that they carry through, to contribute to canyon cutting on the east.

NATURAL STORAGE BASINS.

But while the old surface is virtually unscored by drainage, it is, on the other hand, extensively pitted with saucer-form depressions. These depressions are quite accurately circular where there is no coalescence, and they range in diameter from a few feet to several thousand yards. The smaller ones rarely coalesce; there appears to be a law of occurrence by which they are spaced apart; but the large basins frequently fall into discernible west-east lines. With these coalescence is not uncommon. Hence, in the west-east direction, approximately, shallow and irregular troughs sometimes extend for several miles.

It has been repeatedly urged that these basins of the uplands might be converted into storage reservoirs for the upland storm water. Though there is obvious absurdity in the suggestion, since they are perfectly adapted to storage by nature and yet accumulate little or nothing, still it should receive attention, if for no other reason than that it is persistently advanced.

Precipitation in a desert is of rare occurrence. A peculiarity of it, however, is that usually it is not light in its fall, but assumes the character of a heavy downpour, abrupt at beginning and ending. It is not necessarily of brief duration; it is on the other hand local. For instance, such a downpour may occur within one township and yet an adjoining township receive nothing. But the township receiving a heavy downfall may be visited by light rains only during several succeeding seasons. Desert stream beds in like manner are subject to sudden floods, and it is by floods mainly that the large results in erosion observed in regions of degradation in arid lands are accomplished; but this vigorous work is performed only at widely separated points, and over small areas, during any single season, and at other points the season following. It is for this reason that a desert region of degradation always conveys the impression of active destructive operations recently suspended, as if by radical and abrupt change of climate.

As their universal sod covering bears witness, the High Plains have

A. DEEP AND SHARPLY CUT BASIN.

B. DEEP AND OLD BASIN.

a precipitation differing from that of the arid belt, in that it is often of a gentle and widely distributed character, though light. But the High Plains are subject to rains of the cloud-burst type also. The basins then become ponded. Because, however, of the infrequent and local occurrence of these heavy rains ponding is rare. Normally the natural storage basins are no more than moist on their floors—enough to produce "hay bottoms" of the taller growing grasses, even in wet years—and usually they are dry. Ponding, in fact, is quite exceptional.

There is no remedy for the difficulty. As a rule there is no surrounding area of the flat surface having natural drainage tributary to a basin, and to create a tributary area would be too large an undertaking. Occasional exceptions are the large basins. The comparatively long slopes of their rims afford opportunity for the initiation of drainage which may develop considerable length in the general direction of inclination of the plain and on the upgrade side of the depression. In such basins water will sometimes accumulate to a depth of several feet. The silt washed in during ordinary seasons, and the puddling effected by the trampling of cattle after ordinary rains, prevent rapid loss by ground absorption. Very nearly the sole loss is by evaporation. In consequence, an occasional basin, here and there, will usually hold some water the year through (Pl. CXXXIV, *B*).

But though the depressions are natural storage basins, they are not natural reservoirs, since they can not be emptied. The plain is too nearly flat; its grade, ranging from 5 to 10 feet to a mile would necessitate too great a length of outlet ditching.

Finally, a storm of the cloud-burst type, which alone has sufficient volume of fall to accomplish local ponding, can not be counted on to occur in the same place oftener than two or three times in a decade.

UNDERGROUND RESOURCES.

We have seen that for any appreciable result in supplemental watering of the High Plains, the mountain streams, even assuming complete storage of both their out-of-season flow and their flood flow, have insufficient volume. That is, the surplus from the western humid region—i. e., the mountains—having first to serve an intervening arid zone, would have nothing left for the subhumid zone. It is equally apparent that there is nothing to be hoped for from the local storage of storm water, since these heavy downpours, in excess of immediate needs and so suggestive of abundance, are much too local and infrequent in occurrence at any given point. In short, there are no surface waters, or run-off, to be drawn upon from either far or near. The question, therefore, at once suggests itself: Are there not water resources underground?

ARTESIAN WATERS.

As soon as it became apparent that from some source, either above or below ground, it would be necessary to piece out the insufficient precipitation, the question of a possible artesian supply was raised. Experimental borings were first made on the uplands, and later in the valleys. No flowing wells were secured from any borings upon the High Plains proper, and only a few, and these of small yield, in the valleys. There was no success, for instance, on the low bottom-land terrace of the Arkansas Valley at Garden; but westward in that valley, close to the Colorado boundary, a light flow was obtained over a small area, just as, farther westward along the valley, up to the base of the mountains, small artesian areas had previously been discovered. Similar unimportant success was had in other valleys, as, for example, the Canadian; but in no case was a flow obtained sufficient for the irrigation of more than a few acres. In several cases of deep boring upon the uplands, in which after passing completely through the thick cover of Tertiary gravels the floor had been penetrated, deep-lying waters with artesian rise were encountered, but their height of rise was never found to be sufficient to produce a flowing well. It would stop short not only of the ground surface, but even of the water plane of the ordinary ground water.

This question of a possible artesian supply sufficient for any considerable result, like that relating to the volume of the mountain run-off, may be completely disposed of in the negative, if considered quantitatively. Mr. Gilbert has shown[1] that to the westward, in the Arkansas Valley, the Dakota sandstone and other possible water-carrying formations do not have uninterrupted extension eastward. Within the dry belt in Colorado such beds are here and there, over considerable areas, exposed by erosion, or have been wholly removed — that is, their intake areas are not wholly in the mountains, but in part lie within the desert belt. In other words, the Dakota sandstone is not here the continuous sheet for great distances it is found to be beneath the plains of South Dakota. Furthermore, extensive deep-well exploration has experimentally developed the fact that its yield, and that of all other porous beds within reach, is slight and has virtually nothing to promise for irrigation.

But even assuming the presence of water-bearing rock sheets, such as sandstone, under impervious covers, such as shale, having uninterrupted extension eastward to a distance as far out as the High Plains, it will become at once apparent, on examination, that the largest possible supply must fall far short of requirements. To obtain a fairly approximate idea of what the volume of that supply may be it is

[1] The underground water of the Arkansas Valley in eastern Colorado, by G. K. Gilbert: Seventeenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1896, pp. 560–574.

A. COX BASIN, NEAR LAKELAND, KANSAS

B. MAP OF COX BASIN AND VICINITY, SHOWING SOD CRACKS.

necessary merely to note, as in the case of the mountain streams again, the relatively small size of the mountain catchment area. The eastward surface drainage is separated from the westward surface drainage by the "continental divide"—an irregular line of high ranges. Erosion in these ranges has in the main exposed granite cores—that is, the region is not one of bedded rocks, slightly inclined merely and deeply sculptured. Such a region, entire, might constitute but a single catchment basin for underground waters—one having a single direction of underground movement—while upon the surface comprising several basins of divergent run-off. The mountain ranges here, however, serve as divides for underground and surface drainage alike.

The areas of actual intake for underground drainage toward the High Plains are relatively very small. They consist either in the outcrops, along the mountain flanks, of the porous rock sheets which, far to the eastward, constitute the deeply buried water carriers; or they may be patches of those porous sheets lying close to the mountains, within the desert strip, from which erosion has removed the impervious covers.

The source of supply of much the greater portion of the artesian water to be found beneath the Plains is precipitation in the mountains, yet we have seen that this mountain precipitation is in the first place moderate only, and that, on the other hand, the greater portion of it runs off.

Arid plains absorb a large part of their rainfall. Upon the High Plains there is virtually no run-off, ground absorption and evaporation disposing of the whole. But in mountains, on rock slopes of high grade, much the greater portion of the rain and snow fall escapes in streams. The annual contribution to the artesian accumulation, in fact, must be very much less than the contribution to run-off.

Artesian water is a stored accumulation—continually subjected to losses by drainage, but continually resupplied. The annual contribution to it is relative y small; its stored volume may in time, however, become large. Nevertheless, the question of practical concern here relates solely to the volume of its annual increment.

For irrigation of the High Plains a large volume of water annually would be required. Taking that volume to be not more than a foot in depth over the whole area, the drawing off of this amount from artesian beds would involve the complete exhaustion of something like 4 feet in depth of saturated rock each year. Exhaustion of the total stored supply therefore, by voluntary flow in amount sufficient to meet requirements in full, even if such a thing were possible, which it is not, would be a matter of only a few years. In much shorter time, and with partial emptying only, "head," or hydraulic pressure, would be so far weakened as to cause the voluntary delivery of wells to cease.

The volume of the annual increment, as we have seen, is inconsiderable; at least it is so in comparison with the volume of water required for complete reclamation. But even this small amount could not be drawn upon to the full. The stored accumulation under artesian conditions is in a measure comparable to that in a lake; there is escape at the outlet equal to the sum of the tributary contributions. The rate of escape, or loss, of artesian water is accurately adjusted to the rate of its replenishment (after saturation of the porous rock sheets has been accomplished); head, manifesting itself by rise in a bore hole, being merely an expression of the heavy frictional resistance encountered during transit through the pervious beds. More strictly speaking, the retarded accumulation in a porus rock sheet is like the water under heavy frictional resistance to flow in a grade-line pipe of great length. The upward pressure is hydraulic, not hydrostatic—i. e., the water, though confined below its natural level beneath a cover, is nevertheless in motion laterally. Only a portion of the original supply, therefore, can be drawn off, diminishing head to a certain safe limit, rather than completely exhausting it. Thus, even under the assumed ideal conditions of far and unbroken extension of water-bearing rock sheets, with like continuous extension above of an impervious cover, artesian water must be rated much below surface run-off as a resource in irrigation.

As appears from Mr. Gilbert's investigations, the assumed ideal condition of uninterrupted extension of pervious rock sheets, with like extension of overlying impervious sheets, does not exist. There is not, in the first place, an unbroken impervious cover; erosion here and there within the arid belt has removed it and exposed the water-carrying beds over considerable areas, permitting upward escape of their imprisoned waters. In addition, deformation along many lines, across their direction of slope, has broken and vertically displaced the pervious beds themselves. In some cases, even, erosion, within small areas, has removed them.

The many attempts to secure flowing wells at the upland surface, everywhere unsuccessful—though slight artesian rise is found to be not uncommon—may be taken, therefore, as experimental demonstration, bearing out the unavoidable inference from the above theoretical considerations, that for irrigation of the uplands there is no artesian resource whatever.

LOCAL ARTESIAN MANIFESTATIONS FROM THE GROUND WATER.

Among the popular notions as to the occurrence of artesian water, it is accepted that such water is always deeply subterranean, that it is never to be encountered in unconsolidated material, and that invariably it has a distant source of supply. In the case, however, of certain artesian developments within the High Plains belt, which have

A. BASIN IN VALLEY, REVEALING WATER PLANE OF GROUND WATER.

B. MAP OF BASIN, SHOWING SOD CRACKS

attracted much attention in that region, it is clear that the phenomena result from causes local to the Tertiary gravels, and acting not upon deep-lying waters, but upon the ordinary ground water, which has its origin not at a distance in the mountains but in the local precipitation.

The one essential condition in the development of artesian phenomena is confinement under pressure beneath a cover. All water in porous material, if filling the pores to saturation, must rest upon a floor—i. e., upon relatively impervious material. Artesian water must, in addition, be under confinement beneath a cover, and will therefore exert pressure upward as well as downward. The cover need not necessarily be a bed of hard rock; it may be an interbedded sheet of clay in an alluvial mass. It may not be strictly impervious even, and there may be also—in fact there usually is—escape in some measure at its down-grade margin. Because of the enormous frictional resistance to flow, so called, in any ground material, however porous, underground water has so slow motion that it accumulates and assumes, or tends to assume, a nearly horizontal position along its upper surface. If an overlying impervious bed have inclination steeper than the inclination of this water plane, its dip may bring it into contact with the latter. Down-grade from the line of meeting of the water plane with the under surface of the more steeply inclined impervious cover the conditions for confinement under pressure will be satisfied. Beyond this line of contact the ground water will be artesian—that is, when a way is opened for it it will rise, seeking to attain the position its surface would otherwise have had. This theoretical surface, not strictly horizontal but gently sloping toward the lower margin of escape, is termed the "hydraulic grade plane."

When, by boring, the cover is perforated, the question whether there will result a flowing well or merely rise to some higher level within the bore hole will depend on what the level of the ground surface may be. If at that point the ground surface happen to lie above the hydraulic grade plane to which the confined water seeks to rise, there can not be a flowing well. At many points beneath the flat uplands there is artesian rise stopping short of the surface; but, as we have seen, there is nowhere a case of rise to the general upland level, or even a close approach to it.

In some instances, however, notably those of the Meade Artesian Basin, near Meade, southwestern Kansas, and of the Yellow House Basin, on the Staked Plains of Texas, where locally the ground surface has been depressed to such extent as to lie below the general water-plane level of the upland ground water, there are flowing wells. Seemingly, in the case of these and other large basins, the one essential requirement for development of artesian phenomena—an impervious cover bearing down the ground water below its normal level—is met by the presence within the unconsolidated Tertiary of clay sheets

having broader extent than the basins themselves, assuming that the basins have had origin in ground settlement rather than in any kind of erosive excavation, and that the included clay sheets of the alluvial mass are therefore basined also.

ORIGIN OF THE BASINS.

This conclusion, that the innumerable hollows in the High Plains surface, large and small alike, are due to ground settlement, rather than to some process either of original construction or of subsequent erosion, seems to be unavoidable. As to the shallow, saucer-form depressions more especially, it is obvious that they are not, for example, the work of running water. From a statement merely that the general surface is uneven, it might perhaps be urged as a possibility that they are survivals of an early faint constructional topography of the stream-built plain, in which subdividing and reuniting currents, running upon broad, low ridges of their own creation, had left low areas between; but the plain is not properly to be described as uneven. Its normal character, despite the great number of basins, is emphatically that of a dead flat upland, lightly pitted here and there, the pits or basin hollows having wide range in size, yet as a rule circular and definitely outlined. That is, there is nothing of the nature of undulation between them; the surface in general is no more affected than would be a sheet of clay lightly dented by marbles of various sizes.

The likelihood of origin by wind excavation can not be admitted, for the surface is too firm. Not only is it protected by a closely knit sod, but the soil beneath is "adobe," comparatively hard. There are occasional sandy tracts upon the High Plains—tracts of traveling sand resting upon the adobe surface—and these have a ridge-and-hollow topography of a quite different type, thoroughly characteristic of wind action; but the sod plains proper, on which appear the basins we are considering, show no dust in the air during high winds, except where cultivation has removed the grass covering and loosened the firm soil. Dust storms are common in the arid belt to the westward; but upon the High Plains, away from settlements, the air blows clear. Furthermore, on their floors and slopes alike the basins themselves, as a rule, are thickly carpeted with grass.

Concentric sod cracks.—There are other small depressions, not broad and shallow, or saucer-form, but relatively deep and bowl-shaped. They occur only in the valleys, not upon the flat plain. In rare instances each of these types will have the appearance of having been newly formed, and in each case the characters which convey this suggestion seem unmistakably to point to origin in settlement of the ground.

With the deeper hollows the feature suggestive of recent ground

TYPICAL "BUFFALO WALLOW."

settlement is a sharply cut rim, the inclosed area having been abruptly dropped. In Pl. CXXX the photographs show, in the one case, a pit of this character; in the other, a bowl-shaped hollow, the marginal escarpment, if there ever was one, having been rounded off by age. Within the shallow upland basins, on the other hand, the evidences of recent progress in deepening are arc-form sod cracks, either following the gently rounded margin, or concentric with it, at varying distances upon the flat plain without. Pl. CXXXI presents a photograph and a map of such a depression, locally known as Cox Basin. The map shows, in addition, a larger basin, the rim of which the smaller one, at some later date apparently, has indented. Because of the occasional occurrence of standing water in these depressions a town near by, now abandoned, was known as Lakeland.

The writer's attention was directed to Cox Basin by a stock grower, after whom the basin had been named, and whose ranch headquarters were in the valley of Crooked Creek near by. He had been accustomed to take advantage of the occasional presence of water in the hollow, during rainy seasons and for short periods thereafter, for pasturage of his stock upon the neighboring dry uplands. During the first few years of his familiarity with the locality there had been no encircling cracks. These had abruptly appeared after a season of unusually heavy rains. When first observed they showed openings only an inch or two in width; but beneath the sod, which stretched before breaking, these openings were found to be wider. In fact, along the greater portion of its length each crack was bridged across. At first, as a rule, the sod bridges were sufficiently strong to support cattle, but continual crossing of them along trails to water had in several instances resulted in their breaking down, with consequent injury to the cattle. At the time of the writer's visit no new cracks, and no growth among the old ones, had been noted for two years. Several still retained their original sharp outlines and a depth here and there of 6 feet or more, but the majority were shallow and grass-grown.

Cox Basin is not upon the uplands. It occurs at a level a little below, within the region of a much larger depressed area. It has, in consequence, drainage tributary to it. For this reason it holds water more frequently and in larger amount than do the upland basins generally. It would seem that to this fact may be attributed the apparently more rapid growth, and the accident of the occurrence at the present time of encircling cracks plainly denoting ground subsidence.

Settlement within the Tertiary.—Appearances indicate basining of the alluvial surface as a consequence, first, of rain water accumulation in initial faint unevennesses of the plain; second, of percolation of this ponded surface water downward to the ground water in largely increased amount from these small areas of concentration, rather than from over the whole surface uniformly, with the result that the allu-

vial mass is appreciably settled beneath the basins only. The inference is at once suggested that this settlement takes place as the combined effect of mechanical compacting of the ground particles and chemical solution of the more soluble particles. Finally, these effects should be cumulative, resulting in the growth noted, since, with enlargement of the basins, concentration of rain water within them will be on an increased scale.

Over comparatively small areas surface effects should be symmetrical, but beneath basins of great breadth—and some have breadths of several miles—the depths of settlement at points wide apart within the same basin, as well as the conformation of the basin rims, should reflect the broader variations of structure beneath. Depths should be least above beds of clay and greatest over areas of coarse channel deposits. The occasional very large basins are in fact invariably unsymmetrical—undulated on their bottoms and of irregular outline. It is doubtful, however, whether the very large, irregular basins are to be explained in this way, as will be developed presently.

Nowhere upon the uplands is the depth of settlement in the case of the small circular basins so great as to reveal the ground water; but these occur also, though less frequently, over the bottom lands of the valleys, where the valleys have not yet cut through the Tertiary to bed rock, and one of these bottom-land basins, selected for illustration (Pl. CXXXII), contains a perennial pond. The pond is without perennial surface drainage into it. It is also without outlet. That it is the ground water, however, exposed merely by local depression below the water-plane level, is clear from the fact that in several instances water is encountered at the same level in neighboring wells.

Caving of the Red Beds floor.—The depth of the Tertiary in the case of this lowland basin, revealing the water plane, is comparatively slight. While, therefore, the presence of concentric sod cracks here also indicates settlement, compacting of the Tertiary in explanation of it can no longer be appealed to. Only where the depth of the Tertiary is great and settlement is relatively faint does that inference seem justifiable. In this particular locality (the upper valley of Bullard Creek, Englewood County, southwestern Kansas) the underlying rocks are the Red Beds, containing salt and gypsum, and the Permian shales, which in south central Kansas carry the famous rock-salt deposits. Farther southeastward, in the heavily eroded fringe of the humid belt where the Tertiary cover has been removed, the Red Beds are seen to be extensively pitted by the breaking down of solution caverns.

Here, then, is a satisfactory explanation of basins in the Tertiary cover where the cover is thin. Where it is thick some different explanation appears to be necessary. The great multitude of the basins are small. They range in size from the so-called buffalo wallows to saucer-form depressions a thousand yards or more across and

A. BIG BASIN, CLARK COUNTY, KANSAS.

B. BASIN HOLDING WATER AFTER RAIN.

with depths at which windmill towers need to be of unusual height in order to catch the wind. They are often, over broad areas, so numerous as to lie within a stone's throw of one another, though, as before stated, there seems to be a law of occurrence according to which actual coalescence is prevented. Yet they may be equally numerous over tracts where the depth of the Tertiary is several hundred feet.

At the surface of such a deep mass of loose material the upward-transmitted effect of caving within the rocks of the floor should be a broad and shallow depression, not a pit. The disturbed mass should have the form of an inverted cone, the base, at the surface, much broader presumably than the depth of the apex, at the point of caving within the floor. Most of the basins, however, are small, indicating points of disturbance at slight depths within the Tertiary itself.

Because the thick, alluvial accumulation is not entirely free from cementation, nor entirely homogeneous in structure, a deep-seated disturbance beneath it might perhaps at first have scattered effect at the surface, as if proceeding from a number of points spread apart, at various shallow depths within it. The basin effects in such case should be grouped, which they are not; and, furthermore, with development, they should eventually merge, forming a single large depression, with irregular outline and uneven floor. While large, irregular depressions exist, they are not numerous, and there is no suggestion in such cases of development out of groups of small ones.

Equal occurrence of the shallow basins where the floor is Cretaceous.—The chief difficulty in the way of accepting caving within the rocks of the floor, in explanation of the saucer-form hollows, is the fact that the Tertiary of the High Plains does not everywhere rest directly upon the Red Beds. Over the greater part of western Kansas, for example, Cretaceous rocks, mostly sandstones and shales to a great depth, constitute the floor; yet small basins are no less numerous there.

The very large and irregular depressions do not have this universal distribution. As has been stated, there is no gradation in size from the largest of the circular forms up to these very large irregular ones.[1] And in the case of the latter, deep-well borings, wherever they have penetrated to the floor, encounter the Red Beds, containing salt or gypsum in notable quantity, either immediately beneath or close beneath. Commonly there is immediate or early change in the color of the material brought up, from a prevailing gray to blood red, after passage through the alluvial Tertiary.

Sink holes.—St Jacob's Well and the Meade Salt Well.—In several instances, associated with the large, irregular basins and occurring close to their rims, are sink holes.

From a point near Meade, southwestern Kansas, the eastern front

[1] An idea of about the maximum size attained on the uplands by basins of the shallow, symmetrical type may be had from Pl. CXXXIV, *B*.

of the High Plains extends northward less sharply defined and not so high. Up to southern Kansas this front is a line of "breaks." From the neighborhood of Meade, however, the breaks cease to be the upland margin, but constitute, instead, a second step within the eroded zone, turning in a curving escarpment eastward and northeastward, until faded out by the general decline in elevation.[1] This northeastwardly curving line, marking a change from comparatively gentle undulation to a topography of pronounced relief, also marks approximately the southern limit of the Cretaceous in Kansas and the emergence from beneath the Cretaceous of the Red Beds, to constitute in turn the floor of the Tertiary.[2] For a distance back of this line, where presumably the Cretaceous is thin, large irregular basins are numerous, while downgrade from it the deeply incised Tertiary has a topographic configuration, not of any recognized plan, but tumultuous and disorderly and imperfectly drained. Here are numerous basin expansions which the traversing drainage obviously has not shaped, by erosion, but which it finds passageway through merely because they have intersecting rims. Erosion has in large measure obscured their outlines, but the most conspicuous suggestion is that of differential settlement, not stream excavation.

Within this zone, 19 miles east of Meade, is Big Basin, approximately circular, about a mile in diameter and 100 feet in depth. It has no drainage out, and drainage into it frequently results in shallow ponding at various low areas over the floor. Notching the rim at the southwest is a smaller basin, also without outlet, and separated from the larger one by a low divide. A short distance to the east is still another, called Little Basin, and on the rim of this is a sharply cut sink hole, St. Jacob's Well.[3] Here, again, the water plane of the ground water is revealed. The floor of Little Basin, close to the foot of its encircling bluff, shows a number of shallow depressions, apparently the nearly healed scars of other and earlier sink holes. St. Jacob's Well has every appearance of having been rather recently formed.

A mile and a half southeast of Meade, and close to the rim of the Meade Artesian Basin, is the Salt Well, locally so called—the largest sink hole of the High Plains region. Here, also, the ground water is revealed.

The sudden appearance of the Salt Well is a matter of history. It dates from March, 1879. Its position is in a broad, flat saddle, between a small hill and the slope from the uplands on the east to Crooked Creek Valley, at a point a little below the opening of the latter out of the Meade Basin. The pit not only fully occupies the saddle, but its encircling cracks cut well into the rising slopes on either hand.

[1] See general map, Pl. CXIII.

[2] See Univ. Geol. Surv. Kansas, Vol. II, 1897, Pls. XLIV and XLVII.

[3] See general map, Pl. CXIII, *d*.

A.

B

ST. JACOB'S WELL, CLARK COUNTY, KANSAS

Near by, to the east, upon the uplands, formerly ran the famous "Jones and Plummer" cattle trail, leading from northern Texas to Dodge, Kansas. A mile or more to the south a branch from this overland route, which in those years was much traveled, passed into the valley for over-night camping purposes. The trail led through the saddle directly across the present site of the sink hole. Cattle trails and road ruts, sharply terminated at either edge, are still discernible. Thus, in this thinly settled country the spot was not off from beaten tracks, but lay literally in the path of one.

Fourteen miles to the north was the small town of Pearlette, now abandoned. The Pearlette Call, in its issue of May 15, 1879, referring to the sudden appearance of the pit, said: "Considerable excitement has been created in this section of late over the discovery of a salt well. * * * Since the 3d of March a piece of ground some 175 feet in diameter has sunk, and the hole is now filled with water to a point 14 feet below the surface. Soundings have shown the water to be from 30 to 75 feet in depth. On the 3d of March a wagon passed over the spot where the well now is, and the ground, which is high, was then hard and firm. The track made by the wagon at that time is plainly visible on each side of the well. On the 26th of March it was found in its present shape."

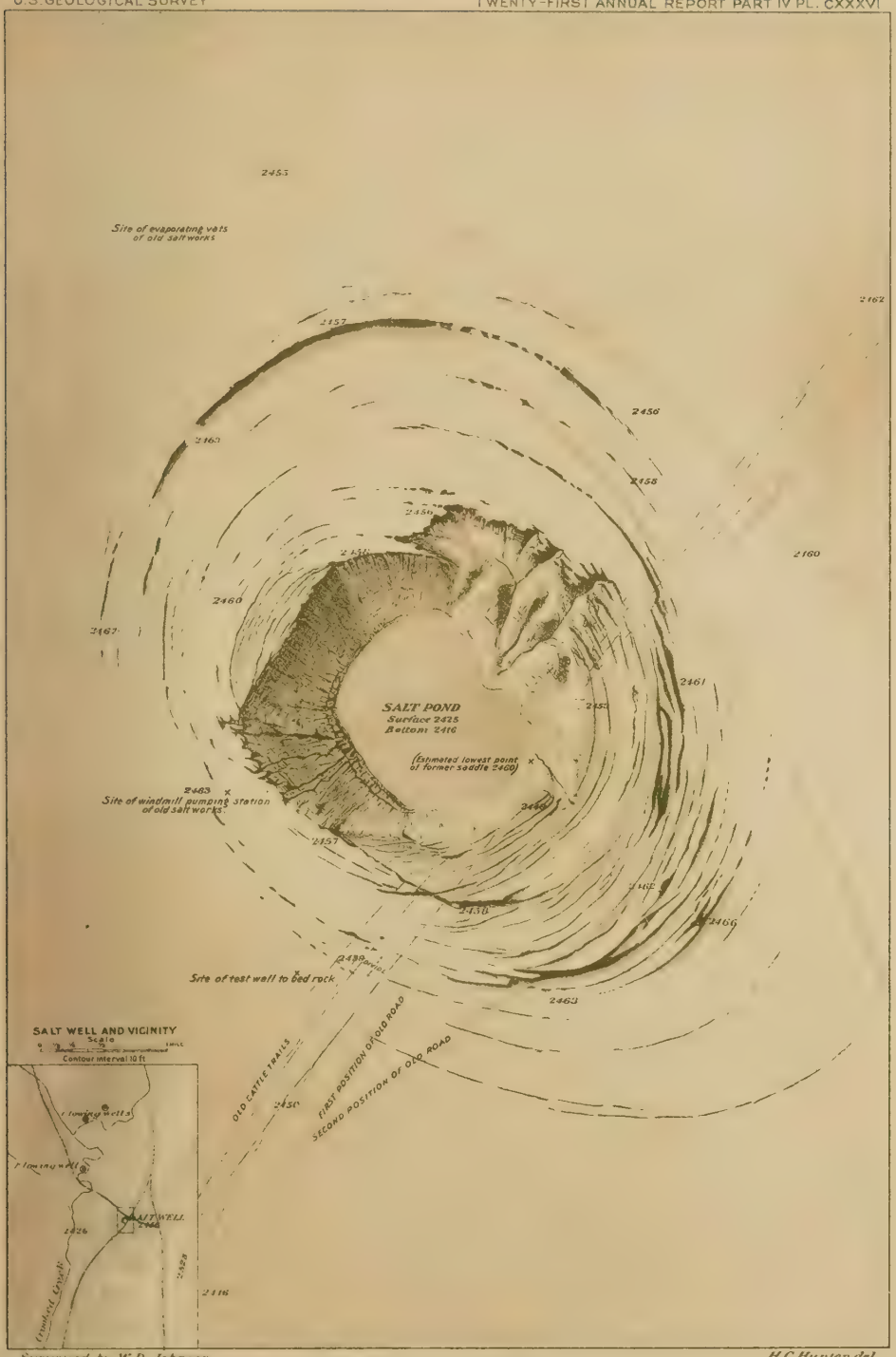
From the first the water in the pit, unlike that in St. Jacob's Well, has been strongly saline, though the ground water in neighboring wells has no taste of salt. A test boring at a point just beyond the outermost sod crack on the south encountered fresh water at a level less than 2 inches above that of the salt pond. An old dug well on the valley slope a half mile to the northeast shows water within 6 inches of the same level. The water exposed in the pit is clearly the common ground water, its level merely lowered slightly by evaporation. As shown by the photographs, Pl. CXXXVII, the ground material here is close textured. It is lightly cemented sandy clay. The passage of the ground water through it must therefore be slow, affording opportunity for evaporation in the open pit to lower the water plane appreciably. As appears from the above newspaper statement, the depth to water at the time of discovery was but 14 feet, with a depth below water to the bottom of 75 feet, making a total depth of 89 feet. The total depth at present, measuring from the assumed former position of the lowest point in the saddle, is 44 feet. From the highest point on the rim, where it has cut into the rising slope on the west, the depth is 44 feet also. The depth to water is 35 feet and the depth in water 9 feet. The pond, along its greater diameter, is 126 feet across. The greatest distance across at the ground surface is 216 feet. The ovalform depressed area surrounding, as outlined by the sod cracks, is 360 by 400 feet. The bottom is 5 feet below the creek bed in the adjacent valley.

The early measurements of depth may not be trustworthy, but it is

probably true that at first the pit was deeper than at present, as well as more sharply outlined, and that it had steeper walls. The testimony of a number of persons now resident in the neighborhood who visited the Salt Well shortly after its discovery is in agreement to the effect that the walls were then unbroken and steeper than now, that there was no apparent ground settlement of an outer zone, and that there were no encircling cracks. In support of the latter statement is a later, shifted position of the old road coming up from the south, to a course which could not now be followed on account of the widely gaping cracks. Apparently filling has taken place to an extent measured by the depth of settlement within the area inclosed between the outermost cracks and the brink of the pit proper. The testimony of early observers also is to the effect that the contained water, standing high at first, slowly sank, reaching about its present level within a few weeks.

The test boring referred to came abruptly upon bed rock of a deep-red color at a depth of 292 feet, after passing easily and rapidly through clay, sand, and gravel (though little of the latter) in alternating layers. The floor was penetrated to a depth of 16 feet. Toward the bottom, while still in the loose material of the Tertiary, the presence of salt began to be perceptible to the taste, and saltness thereafter increased.

A curious fact in connection with the Salt Well is that its strongly saline water at times has a high temperature—according to common report, close to the boiling point. The temperature of the ground water in this region, winter and summer, varies less than a degree from 59 degrees. Where exposed, however, as on Bullard Creek, it falls in winter, especially in cloudy weather, approaching that of the air. In winter the high temperature in the Salt Well falls also. During a period of freezing weather in January the writer found it cold to the hand both at the surface and as brought up in a bottle from the bottom. But in July a bottom temperature of 156 degrees was obtained, and this held to within 3 feet of the surface. Near by, in the test boring, at the same level, it was only 59 degrees, the prevailing ground-water temperature. The temperature of the upper 3 feet in the Salt Well at the same time was 89 degrees, and the air temperature 94 degrees. The water was found to be stratified, according to the density of its saline content; that is, an upper layer, 3 feet in depth, and at all points within this depth, contained about one-third less salt per unit volume than the remaining 6 feet, extending to the bottom. The surface of the lower stratum, and the plane of contact between the two, was definitely marked by water-logged twigs and grass stems, which the wind had brought in and which had sunk in time through the comparatively fresh water, but hung suspended with their upper ends at a uniform level in this nearly saturated solution


Site of evaporating vats of old salt works
SALT POND
Surface 2425
Bottom 2416
(Estimated lowest point of former saddle 2460)
Site of windmill pumping station of old salt works
Site of test well to bed rock
OLD CATTLE TRAILS
FIRST POSITION OF OLD ROAD
SECOND POSITION OF OLD ROAD
SALT WELL AND VICINITY
Contour interval 10 ft
SALT WELL
Crooked Gorge

Surveyed by W.D. Johnson

H.C. Hunter, del.

THE SALT WELL

SCALE OF FEET
0 50 100 150 200 250

Figures indicate elevations above sea level

beneath. Some weeks later, after several days of cloudy weather, no rain having fallen meanwhile, the water temperature at the surface was 76 degrees, and at 6 feet below only 98 degrees. Further observation and experiment led to the conclusion that the much higher temperature of the lower stratum is due to the storage of sun heat, the upper layer of comparatively fresh water acting after the manner of the glass covering of a greenhouse, permitting direct rays of the sun to enter and warm the salt water below, but preventing the escape of reflected rays.

The layer of comparatively fresh water would seem to have been extended across the other from the surrounding ground water. Presumably the raising of temperature in the salt water beneath did not lighten the latter sufficiently to overcome entirely its superior weight, due to the contained salt. During progress of the sinking to bed rock in the test well near by a record of temperatures was kept. As in borings everywhere, there was increase with depth, but it was slight.

It was surprising that there should be stratification as between the brackish water and the brine; it is not clear why, if the salt comes from below, impregnating the fresh water above, it should stop short of the ground-water surface. It has been suggested, since borings to a depth of from 100 to 200 feet in this neighborhood usually encounter artesian water, rising to a level sometimes above and sometimes below the ground-water plane, that the upper level of the salt water here marks the local artesian grade plane, and that artesian water, carrying salt, has risen merely to its level of equilibrium. The case here is not parallel with that of a tubular well in which the ground water, after its floor has been reached, is "cased out" by the tube. The Salt Well below its actual bottom presumably continues, in effect, as a loosely filled-in shaft, affording comparatively free passage for water, because the Tertiary structure, containing clay sheets, is broken down. The ground water is not cased out. It extends through the Salt Well and across the perforation in the artesian cover beneath. Hence, on this assumption that the water plane of the ground water has a higher position than the artesian grade plane, there should be downward passage into the artesian body, rather than rise from the latter into the overlying ground water. In principle the case is like that of a bucket of water suspended in a larger vessel filled to a little below the level in the bucket—upon removal of a plug in the bottom of the latter, flow will be downward.

As shown on the map and in the accompanying photographs (Pls. CXXXVI and CXXXVII), there are old shore lines about the pond, at slight elevations above the present shore, indicating fluctuation in level. The total range seems to be greater than that of the seasonal fluctuation of the ground water. It may be accounted for in part by evaporation on the one hand, and rain-water contribution on the other.

The horizontal ground-water movement in such close-textured material is exceedingly slow under these light heads. In another instance, where a basin in a valley bottom exposed a broad surface of ground water, also in clay, the writer found a lowering of nearly 3 inches below the surrounding water plane, as determined by test borings. It was clearly an effect of evaporation, which had continued through several weeks of cloudless hot weather just preceding. The basin had a small drainage area tributary to it, and some days later, immediately following a heavy rain, it was found that the relative positions of pond surface and water plane had been reversed, the former standing about an inch above the latter. The time required thereafter to establish equilibrium was nearly two days. Probably the greater fluctuations have half-yearly intervals, the summer level being, as a rule, low and the winter level high.

In the case of the Salt Well, the tributary drainage to which is insignificant, the losses probably greatly exceed the gains. The direction of easiest movement of water here is vertical, since vertically beneath the ground is broken, and recovery from the recurring losses, therefore, should be continually from below. It is possible that the effect of this continual upward resupply is to lift the low-lying salt water, and that at the time of the observation noted its summit elevation fell short of the pond surface by 3 feet.

The assumption is made that the Salt Well has had origin in caving within the Red Beds floor, and that a cavernous opening there had been created and subsequently broken down through removal in solution of an interbedded salt deposit. This type of depression is strongly in contrast with the saucer-form hollows, though the latter at times also exhibit the phenomena of concentric sod cracks. The sod crack is evidence of ground settlement, with a horizontal component—that is, it is merely the most prominent sign of a shallow land slip. Land slipping has followed upon the sudden caving of the Salt Well, the comparatively loose Tertiary gradually moving in from all sides to fill the pit. It might be supposed, in like manner, to mark a broadening and fading out in the case also of the shallow basins of the uplands. But while the sod crack always means land slipping and filling, the fact in this latter case seems to be that it is an evidence of deepening and growth rather than of the commencement of healing. Along the slopes of arroyos, where they make back into the eastern border of the High Plains, and about arroyo heads, it is almost an invariable accompaniment of erosion. Pl. CXXXIX, *A*, shows an arc-form sod crack at the head of a faint arroyo. In fact it is apparent in many instances that the numerous broad and shallow drainage lines of the upland border, grass-grown and without a central ditch, are due more to subsidence and creep than to erosion proper. The arroyo bottom is commonly marked

A

B

THE SALT WELL

by chains of pit holes, as in Pl. CXXXIX, *B*, culminating at times in depressions so large as to pond and hold the total of its maximum flow, thereby checking further extension. These effects are obviously the result of the action of downward-percolating rain water upon open-textured ground material above the level of permanent saturation. To any interested observer having wide familiarity with the High Plains surfaces it would seem that the conclusion must be inevitable that the small saucer-form hollows, away from arroyo connections, are equally the effects of surface waters acting at shallow depths within the Tertiary, compacting and settling it at points, as the arroyo drainage does along lines.

The sink holes, such as St. Jacob's Well and the Salt Well, also the great depressed areas, such as Big Basin and the much larger Meade Basin, to be considered presently, may be attributed to caving, resulting from removal of soluble masses within the underlying rocks. The sink hole is a detail merely, illustrating this process. As a topographic form it is necessarily ephemeral, as note the rapid closing of the Salt Well. Quite likely the gradual basining of a large tract witnesses the appearance and disappearance of many sink holes. Apparently the bowl-shaped hollows are their scars. But the innumerable upland basins, especially where the floor is Cretaceous to great depths, are clearly to be ascribed to grain-by-grain processes of readjustment and compacting, at work within the Tertiary only.

To this view it might be objected that elsewhere extensive alluvial surfaces do not exhibit a like faint topography of symmetrical hollows. But the subhumid High Plains, as we have seen, are exceptional in that they are virtually without surface run-off and are not subjected to erosive action. They would thus seem to afford exceptional opportunity for the working out of appreciable or visible results by a feeble process that possibly after all is in some degree operative upon alluvial plains everywhere, though relatively impotent in humid lands because there brought into competition with erosion.

Disorderly topography of the "breaks."—Caving v. erosion.—The topography of southwestern Kansas below the line of breaks referred to is not only tumultuous and disorderly in detail and imperfectly drained, but it rapidly softens down here and there into broad expansions, not without through drainage, and in a measure modified into some semblance of stream valleys, yet obviously not the work of stream erosion. Such an area occupies something more than 100 square miles in southern Clark County. The town of Englewood lies within it, near the western border. It extends also into Oklahoma. The Cimarron River enters and leaves it, in each case between low canyon walls; the Big Sandy discharges upon it, and, in flood, manages to struggle across; Fivemile Creek fades out entirely upon it, and the headwaters of Bul-

lard Creek are decapitated at its western margin by the comparatively recent small depression already referred to. It is being built upon, rather than excavated, by much of its tributary drainage.

Shortly after passing out of the Englewood Basin, the Cimarron enters Oklahoma again and issues upon the Salt Plain. Here is another low area which, obviously, from its configuration, is not explainable by erosion except in a secondary way, although erosion has been vigorous in the surrounding hills.

The drainage of the entire region is more or less brackish, from dissolved salt, or hard, from dissolved gypsum. Where the Tertiary cover remains, disorderly tilting is frequently in evidence in the variously inclined positions of the mortar beds. Where erosion has removed the Tertiary, exposing the Red Beds, inclined beds of gypsum often bear witness also to diverse tilting.

In the "gypsum country," to the south of the Salt Plain, caving is visibly in progress. Occasional interstream areas, thinly mantled with alluvium, are extensively pitted by funnelform sink holes, and some of these connect by open shafts with underground drainage systems, which follow intricate courses along beds of gypsum, contributing eventually to the deeply incised surface streams, from openings in their canyon walls. The lighter surface drainage is sometimes disarranged and diverted from former courses, still plainly traceable, by settlement of cavernous expansions along these underground channels, creating basins overhead and sink-hole openings, into which sometimes the surface streams disappear. (Pl. CXLII, p. 720.)

THE MEADE ARTESIAN BASIN.

There are no large depressed areas in the "gypsum country," however. These lie to the north, where basining appears to proceed rather by the displacement of salt deposits on a large scale. Below the margin of the Cretaceous, where the Red Beds take its place as the Tertiary floor, the whole region to a greater or less extent has been affected by differential settlement. Back a little from the margin, where the Cretaceous is yet thin, or else where post-Cretaceous erosion possibly had removed it in embayments, there are individual basins, surrounded wholly or in part by flat uplands. Head-stream sapping, carrying back the upland escarpment, in several instances has cut into these, establishing drainage out. Among large basined tracts of this marginal type are Scott Basin and the Meade Artesian Basin. Centrally located, however, upon the great plateau of the Staked Plains, are the two others, previously mentioned—the Silver Lake and Yellow House basins[1]. Cheyenne Bottoms, in central Kansas, well to the east of the High Plains, a rudely circular depression about 8 miles in diam-

[1] See general map, Pl. CXIII, *a*, *b*, *e*, and *f*, for the positions, respectively, of these four large depressions.

SOD CRACKS ENCIRCLING SALT WELL.

eter, though with a gap in its rock wall on one side, is quite possibly also a basin of subsidence[1].

As to the Silver Lake and Yellow House basins in the interior of the Staked Plains plateau, it is not known that the Red Beds there lie immediately beneath, or close beneath. It can only be inferred that they do. Well borings have not penetrated to the floor. But, like the Scott and Meade depressions, these two are distinctly different in type from the saucer-form hollows which abound there also, in that they are very large, unsymmetrical, and of uneven depth. Like the Meade Basin, they exhibit the phenomenon of artesian rise in wells stopping short of bed rock, and therefore wholly in the Tertiary. The wells which show rise to the surface, however, are several only, and have feeble flow.

The floor of the Meade Basin comprises about 55 square miles, or 35,000 acres. This artesian area at one time excited wide interest over the High Plains. There seemed to be offered the prospect, not only of rich irrigation development of a considerable tract, but of artesian relief in like manner for other large depressed areas and shallow, broad valleys. The prospect was all the more enticing because the Meade wells were of comparatively light depth, not in hard material, and therefore inexpensive to make. Owing to the widely accepted notion that all artesian waters are, of necessity, far derived, it was assumed withous question that the artesian stratum here discovered was universally extended beneath the uplands, though without sufficient head to reach to the general upland level. On such an assumption there should be rise to some height in wells upon the uplands everywhere. On the contrary, it is found that there is no universally extended artesian stratum, and no rise in wells whatever except where, under a rare combination of peculiar and favoring conditions, it is locally developed from the ordinary ground water.

In the case of the Meade Basin these requisite conditions are present and exceptionally favorable, and there is artesian rise in borings sufficient to produce flow; but this voluntary delivery at the surface has origin in the same vastly extended body of water which wells upon the uplands everywhere encounter, inert, at almost prohibitive depths. The facts all point unmistakably to local basining of the water plane, by depression of a broad interbedded clay sheet of the Tertiary,

[1] It is ascribed by Professor Haworth to stream erosion. He says: "In addition to the streams already described a number of smaller ones of considerable local interest occur. A few of them have peculiarly shaped valleys of erosion, which are different in some respects from any features connected with those described, in that wide, short valleys of the fry-pan form are produced. The best developed instance of this kind is in the Blood Creek Valley, near Great Bend, locally known as Cheyenne Bottoms." (Univ. Geol. Surv. Kansas, Vol. II, 1897, p. 42.) It should be noted, however, that the famous Kansas salt mines are not far distant. Also, that caving is not unknown to this region is shown from the fact that in 1898 a sink hole suddenly appeared, within a night, at the railroad station of Rosel, 40 miles to the southwest, carrying down several of the station buildings, revealing in their place merely a pond, at a depth of about 70 feet and about an acre in extent, surrounded by abrupt walls.

resulting apparently from extensive caving and settlement within the Red Beds, beneath. Depression of the upland surface to a level below that of the water plane is not alone sufficient. There must be coincidental occurrence of the interbedded clay sheet. In the case of the small basin hollow shown in Pl. CXXXII, across which the water plane is extended undisturbed, this impervious stratum presumably is absent.

Widely extended beds of clay or sandy clay are not uncommon. Naturally they make up the larger part of the so-called "Tertiary gravels." In alluvial building they are the deposit of the fringe of the stream network. As we see in the case of modern plain-making streams, the shifting courses nevertheless shift slowly, and the slack-water lagoons even may have considerable persistence, depositing fine silt. There will be interwoven channel deposits beneath, and in time channels are certain to take shifting courses again above. The wells of the Meade Basin, like those of the several other basins mentioned as developing artesian phenomena, reveal such sections. In many other depressed areas, as also upon the uplands frequently, borings encounter only sands and gravel to the bottom.

Ordinarily no inference as to the possibility of occurrence of upward pressure in underground water is to be drawn from local topographic configuration. It is true merely that the lower the ground surface the greater the likelihood that a known upward pressure will be sufficient to result in a flowing well. As commonly employed, the term "artesian basin" does not necessarily imply corresponding basining at the surface. In the case, however, of the several relatively small areas of the High Plains, which have flowing wells, such as the Meade Basin, it does. There local ground settlement is primarily the cause of artesian development. The depressed areas are artesian basins precisely for the reason that they are basins topographically. Where there is flow at all it will be found that two requisite conditions have been satisfied: the floor lies below the surface level of the ordinary ground water; and beneath the floor again, serving as a cover, is a clay sheet, or connected grouping of clay masses, basined also. This clay sheet, interbedded with the more open-textured Tertiary material, must have broader extent on all sides than the depressed area, and a marginal depth beneath the uplands less than that to the free water plane. The actual basining of the ground water is effected by the clay sheet. Strictly speaking, the artesian basin is that of the under surface of this buried impervious, or relatively impervious, stratum. It is definitely limited by the line of dipping contact of the impervious stratum with the water plane. The area of artesian effect is that within which water will rise in wells which open a way for it. The area, however, within which there will be rise to the surface and flowing wells will be smaller,

A. SOD CRACK AND LAND SLIP.

B PIT HOLES ALONG ARROYO

and it will rarely happen that the floor of the superficial basin will be low enough to result in any flow whatever.

The sunken area at Meade is not without outlet. It is traversed by Crooked Creek. As the map shows, its floor has the form approximately of an isosceles triangle. The length of the base from *a*, near Wilburn, to *b*, near Meade, is 19 miles. The creek, when it flows at all, follows this long line with barely perceptible motion and in broad meanders. The greatest width, from the third point, *c*, to about the center of the base, is 7 miles. In this direction, due southeast and at right angles to the course of the stream, the floor is gently inclined, though to the eye, because of its great extent, the inclination is not apparent. It is faintly concave as well. The total fall is about 100 feet; 80 feet of this fall, however, occurs in the first third of the distance. The final third is nearly horizontal, though containing shallow secondary basins. This faint southeastward slope is terminated by relatively abrupt rise again to the upland plain. The mean grade of the hollowed profile is 14 feet to a mile.

Critical examination of the region, especially of the south and east, brings out the fact that the basin has been tilted, and that in this tilting and settlement the eastern embracing arm of uplands has shared. The traversing stream or creek bed—it is a stream for only a few days in the year—has been diverted from a course a little north of east and turned sharply backward toward the southwest. It enters the triangular basin area, not at the highest point of its hollowed and tilted floor, but at one end of the long side, and it follows along the flat zone there across the direction of general inclination.

Its mean grade in the 19 miles, as measured on a direct line from *a* to *b*, is 4 feet to a mile. The actual distance along meanders is 27 miles; the true mean in consequence is less than 3 feet. For a considerable part of this distance, beginning near the middle, the course is nearly horizontal, and here the stream has built up its bed, natural levees following its meanders.

In detail, the floor has faint undulation, or, more properly, coalescing basin hollows. In the last two or three decades these hollows have several times during brief flood stages of the stream become filled with water. The creek at such times has in large part wholly abandoned its single defined channel, subdividing and wandering broadly, spreading sands, or lingering for days and weeks in slackwater expansions and ponds without outlet, depositing silt.

The vastly extended uplands on the west have gentle inclination eastward, or a little to the south of that direction. The embracing arm of high flats on the east is seemingly to the eye a brief extension without deformation of this great plain. Its mean width is about half that of the basin it incloses. The "breaks" mark its outer or eastern limit, from which descent to the uncovered Red Beds along

stream lines is rapid. Opposite the basin this southwestwardly turning arm of upland is found to be hollowed. Here, also, stream-head sapping along the irregular line of breaks has most narrowed it (*d*, on Pl. CXLIV, p. 724).[1]

The western uplands show bending in a double curve to the basin floor, rather than abrupt termination at a rim. The fold is steep, and it has been incised by erosion; but in profile along several lines it may still be made out.

On these profiles at one or more levels there are indications of terracing, and toward the basin outlet at Meade a terrace of this character broadens to a narrow intermediate plain. The obvious suggestion that Crooked Creek at one time had filled the basin, creating a lake which had left shore lines, and that eventually this lake had cut down an outlet, is not however to be entertained. The flood stages of the upper creek endure for only a few hours, and the intervals between floods are years. The assumed body of water would have had to have great depth and an area but little less than the catchment area of the stream above. The actual flooding noted is comparatively trivial in volume. It is the measure very nearly of the total inflow at each flood period. The escaping stream, which usually has continued to flow for several days after inflow had ceased, is merely its drainage off. The terracing would seem rather to indicate stages of basining and successive reductions of the affected area in the successive stages.

Settlement is in the main responsible, apparently, for the narrow arm of the depression extending northward from Fowler to Wilburn. It would seem that it might be taken in like manner as accounting for the arm extending out of the basin southward, forming for a space the lower valley of Crooked Creek. This lower arm does not have the smoothly hollowed cross section of the upper one, though its grade is hardly less gentle. It has strongly incised tributary arroyos, and is itself modified into a fair semblance at least of a normal valley of erosion. There are, however, especially on the west, toward the arroyo heads on that side, descending profiles again of the upland surface, showing in arroyo sections mortar beds and the original alluvial bedding planes bending down to the eastward, just as in the breaks elsewhere there is evidence of settlement in lines or chains of basins, determining and controlling drainage.

The upland strip lying to the east of the Meade Basin continues southward, walling in Crooked Creek Valley on that side also. The eastern breaks here head the many tributary valleys of the Big Sandy. Sand Creek, the southernmost of these tributaries, has cut backward toward Crooked Creek, at right angles to the course of that stream, until only a neck of uplands, about a mile in width, intervenes (at *e*, and southward). About its head the upland surface dips toward

[1] See also U. S. G. S. Topographic Atlas U. S., Meade quadrangle.

A.

B

THE SALT PLAIN, CIMARRON VALLEY, OKLAHOMA

it noticeably, the distinction between erosion grades and the broad slopes of original basining being conspicuously marked. At the point of outlet of the Meade Basin, there are bluffs for a space on either side, and these show bedding, cut across. The actual notch, constituting the outlet, is clearly the product of erosion, but lower Crooked Creek here, like Sand Creek, which seems destined in time to work through the narrowed uplands and behead the other, has tapped the basin. Eventually the narrow upland strip will be eaten through at many points; the line of breaks will then be immediately advanced the 7 miles across the Meade Basin to the front which now constitutes its western rim, and the basin will become subdivided among the several capturing streams, adding merely another group to the anomalous valley expansions within the zone of breaks.

The Meade Basin was originally a large and irregular sunken area without outlet, like that at Yellow House in the interior of the Staked Plains; but, occurring near to the upland margin, it has suffered from the combined effects of marginal settlement and head-stream sapping. By regional tilting eastward its floor has been given inclination in that direction; the narrow table-land on the east has been unevenly settled and tilted also, and erosion encroachment has already on the south made a breach. Its distinctive character as a basin of settlement, not a "fry-pan" valley of excavation, is in large part preserved. As an unusual topographic form, of an essentially evanescent type, it is in an early stage on the way to obliteration, just as the Englewood Basin—the lowland area in the breaks of southern Clark County, traversed by the Cimarron—has reached a late stage, and is obsolescent.

Upon the uplands west of Meade the depth to the free water plane is about 50 feet. Ground water has movement; though continually renewed, it nevertheless continually drains away; its surface therefore has slope. Under any broad alluvial table-land, and back from the marginal lines of escape, both the direction and the grade of this slope will commonly approximate that of the ground surface. West of the Meade Basin both the uplands and the water plane normally have eastward inclination, and the grade in each case is about 10 feet to a mile.

Extended across the Meade depression the water plane should pass high above the floor—70 feet above at the western border, 90 feet above at the center, and 40 feet above at the eastern border. Eastward tilting has been greater by 30 feet than the original eastward inclination of the surface.

If the Meade Basin were completely inclosed, the uplands extending far beyond, and if the artesian "cover," or interbedded clay sheet, were strictly impervious (which it is not), permitting of no upward leakage in springs (which in fact it does), this water plane, extended

on its 10-foot grade, would be the artesian "grade plane." Wells at the points mentioned, for example, would have rates of delivery to be measured, respectively, by these heads of 70, 90, and 40 feet. That is, in pipes, continuing the well tubes upward, the rising water would come to a stand at these several altitudes.

The relative elevations of all the flowing wells in the Meade Basin were carefully determined by leveling.[1] Rates of delivery were measured at a small number of selected wells, their heights of rise to a stand being ascertained at the same time. As will be seen, the wells occur in groups. None of them have strong flow, or high rise in standpipes, the highest rise being 22 feet. By comparison with tested wells the mean deliveries and heights of rise in each group were estimated. The map shows the positions and elevations of 209 flowing wells. Those of a few others, of insignificant yield and having scattered distribution, are not shown, though they were obtained. They have useful bearing, however, upon the position of the hydraulic grade plane. Depths to standing water, also, were determined in five other

FIG. 318—Hypothetical section of rim of Meade Basin.

wells (marked P, indicating "pumping wells") occurring within the bordering zone, where there is artesian rise, though not sufficient to reach to the ground surface. Among the groups of flowing wells the experimental heights attained in standpipes have considerable range. This was found to be largely due to imperfect casing, permitting leakage into the porous ground overlying the "cover," the usual tubular lining frequently having been omitted wherever the lightly cemented ground material proved to be strong enough to maintain an opening without it. For fairer comparison with the scattering individual wells, therefore, means were taken. The resulting hydraulic grade plane, indicated on Pl. CXLIV by dotted contours, may, however, be accepted as closely approximating the true one. The figures on the contours are restored from the means and represent the assumed true position of the grade plane. Altogether this generalized theoretical surface is based upon 226 precise ground-surface elevations, having range as follows: Southwest to northeast, +76 feet; southeast to northwest,

[1] The accompanying map of the Meade Basin (Pl. CXLIV) has been prepared, in its general outlines, from the data of the Meade quadrangle, U. S. G. S. topographic atlas. The positions of wells and their elevations, however, were obtained from original meanders and checked levels by the writer's assistant, Mr. Dennis D. Doty.

A.

B.

TILTED MORTAR BEDS.

+86 feet; southwest to northwest, +128 feet; from the center of the floor to the highest flowing well at its margin, +96 feet, and from the center to the lowest flowing well, −32 feet. To these, in order to determine the hydraulic grade plane, plus or minus corrections have been applied, mainly by estimate, but within a measured range of only 22 feet, and therefore subject to small probable error.

The true position of this surface of equilibrium to which the basined ground water seeks to rise in well borings is of interest mainly as revealing hollowed deformation, rudely corresponding with that of the topographic surface. Theoretically, as we have seen, it should be an inclined plane, identical with that of the upland ground water, extended. There is, in fact, inclination in the same direction, but the inclination is steeper, the general level is lower, and the profile of the slope is hollowed. The hollowing appears to be due to leakage through artesian springs rising from the basin floor in the region of lowest depression and strongest upward pressure. As above stated, the normal water plane, extended, would pass 70 feet above the floor at its western border, 90 feet above at the center, and 40 feet above at the eastern border. Along this line, at the same points, the actual rise is, however, only 2, 18, and 4 feet, respectively. The hydraulic grade plane, in fact, barely skims the surface. It does so as a rule only where the surface is itself, in many places, basined in a minor way. Here occur the groups of flowing wells, with maximum rise of a little more than 20 feet. The faintly domed areas between the minor basins it slightly underruns, and here, on the other hand, the artesian rise falls short of the ground surface.

The direction taken in this region by the line of breaks, or erosion margin of the uplands, is southwest-northeast. The drainage heading at the breaks, made up of the many branches of Big Sandy, Bear, Bluff, and the smaller creeks, has courses at right angles to this line, southeastwardly to the Cimarron. Above Wilburn, Crooked Creek, as we have seen, has a course a little north of east, and seems at one time to have been tributary to the Arkansas. The backward turn it makes at Wilburn, and which it maintains not only to Meade, but for 12 miles beyond, to Odee, gives it a course directly away from the Arkansas for 30 miles. Along this 30 miles it parallels the line of breaks, with a narrow strip of upland intervening. It does not run in a canyon, except in the brief passage through the notch at Meade. From Meade to Odee, as from Wilburn to Meade, it follows along the foot of a limiting bluff at the eastern border of a broad, basin-like expansion, tilted toward the southeast. At Odee, however, it turns directly against the strip of upland, and, cutting through it, joins the parallel system of Cimarron tributaries. In this change from the Arkansas system of drainage to the Cimarron system, the middle 30-mile section of Crooked Creek forms, with the other two, a great letter Z.

The valley of Crooked Creek is normal and sharply cut from its termination upon the broad Cimarron bottom back to Odee. It is an ordinary valley of erosion also from Wilburn to its source. But from Odee to Wilburn, along the middle arm of the Z, the low-lying area which it traverses is obviously not a stream valley at all, and only in its minor configuration a product of erosion. Below Meade a second oval-form basin of settlement is extended southwestward, fading out a few miles below Odee. The shallow notch at Meade is a product of erosion, by backward cutting, connecting the two depressions, and the opening at Odee is another, establishing through drainage. The original Crooked Creek below Odee was a short stream, like Sand Creek, heading in the breaks against the narrow strip of upland. By sapping it has worked its way through.

The Odee basin is deeply incised by arroyos tributary to Crooked Creek, coming in from the west. Along their side slopes, at various points, these show eastward dip of bedding planes and mortar beds of the Tertiary, and well borings almost invariably develop the phenomenon of artesian rise. In several instances, also, these long drainage lines, though dry in their upper courses, have perennial flow lower down from artesian springs. The northernmost of the series, Spring Creek, appearing at the southwest corner of the map (Pl. CXLIV), carries through to Crooked Creek, which it sustains as a perennial stream for several miles. A number of the spring sources of Crooked Creek issue with considerable force from beneath impervious layers, either clay masses or mortar beds. A comparatively light spring of this character, on the north slope of the Canadian Valley, in northern Texas, has been walled in. It rises about 4 feet, at which height it ceases to flow. This level, however, is constantly maintained, though the spring is continually resorted to for drinking purposes by large numbers of cattle.

A spring so placed at the folded margin of a plateau having interbedded impervious sheets will mark the lower limit, very nearly, of the hydraulic grade plane if the ground water happen to be confined by the folded sheets. The ground water normally has dip from an upland to a valley, and if descent of the ground surface be too rapid, and if there are no impervious layers interposed, it may pass out at the surface before the foot is reached, resulting in visible drainage off in the form of springs. But if the slope is not the product of erosion, but is the rim of a settled area, with underlying clay sheets inclined also, the ground-water surface will be forced into a position steeper than it would normally assume. Wells sunk to it then will show artesian rise (as at *b* in fig. 318), and springs in arroyo indentations near the foot will be of the upward-boiling variety—that is, they will be artesian.

Of the two basins, the lower one is the older and the more advanced

MAP SHOWING INTERFERENCE OF UNDERGROUND DRAINAGE SYSTEM WITH SURFACE DRAINAGE.

in transformation by stream erosion. Toward its gateway of escape Crooked Creek has cut through the Tertiary, exposing the Red Beds floor, and the margin of artesian escape has, in consequence, been carried some distance upstream, not only on the main creek but along several of its tributaries. The Odee basin has no flowing wells, but above the margin referred to wells generally have artesian rise. Possibly there may have been head sufficient for flowing wells originally, as in the case of the Meade Basin at present. There the Red Beds floor, as indicated by the test boring near the Salt Well, is still covered by about 300 feet of Tertiary. Stream incision of the Tertiary has weakened the artesian head; eventually it will, by this process, be completely destroyed.

It thus appears that the phenomenon of rise of water in well borings is not confined to the so-called Meade Artesian Basin. A much larger area, including it, is involved. There is a narrow zone on the west in which wells exhibit rise, in rapidly diminishing amount, backward to the undisturbed ground-water level. This zone broadens southward, extending some miles beyond Odee; but it also has broad extension eastward, including the upland strip, which has been settled bodily from its proper level, as well as much of the eroded Tertiary of the breaks, descending to a thinned margin upon the uncovered Red Beds. Just above this margin, in the valley of Sand Creek, 5 miles southeast of Meade, is a group of feeble-flowing wells, at an elevation 60 feet below that of the southernmost flowing well in the Meade basin. Here, too, mortar beds, as well as original bedding planes, not only bear witness, in diverse tiltings (Pl. CXLI, *B*), to caving in detail, but by their general southeastward inclination testify also to general marginal settlement.

This settlement has occurred, determining the line of breaks, where the Cretaceous, which to the northwest is thick, thins out southeastward, leaving the Tertiary resting directly upon the Red Beds with their included soluble deposits of salt and gypsum. The depressed area back of the line of breaks, of which the Odee and Meade basins are the lowest portions, merely appear to mark the site and general outlines of an erosion embayment in the Cretaceous margin.

In a discussion, in 1897, of the origin of the Meade Basin, in one of the Water-Supply Papers of the United States Geological Survey, Professor Haworth ascribes it to faulting.[1] Under the subtitle, "Crooked Creek Valley and fault," pages 22 and 23, he says:

> These peculiar physiographic conditions in the vicinity of Crooked Creek, in connection with geological data gathered from wells, led the writer to conclude that local deformation had produced them. * * * The general upland plain, from 8 to 12 miles to the west of Crooked Creek, both physiographically and geologically,

[1] Underground waters of southwestern Kansas, by Erasmus Haworth: Water-Supply and Irrigation Papers U. S. Geol. Survey, No. 6, 1897.

corresponds with the plain on the east of the creek, which approaches to within less than a quarter of a mile of the creek valley. The general appearance from Meade southward is that of a fault, with the western wall dropped and Crooked Creek occupying a position over the fault line. Northward the whole artesian valley seems to have been dropped downward, leaving an abrupt wall on the west and a more gentle wall on the east. Standing anywhere in the valley one can see the wall all around. On the west it is considerably over 100 feet in height, while to the east it is somewhat less, but still very perceptible. We have here a valley occupying about 60 square miles, which is so different from anything else known in this part of the country that it is exceedingly difficult to explain its origin by attributing it to erosion. The peculiar position of the creek is likewise hard to explain by ordinary erosion. The sharp angle at Wilburn, and the southwestern direction for nearly 20 miles across a plain sloping to the southeast, are certainly very remarkable, and probably have a cause different from that which ordinarily determines the location and direction of streams. But, if in post-Tertiary times a triangular area, equaling in size and position the present artesian area, could have dropped 100 feet or more with a single fault line extending southward to beyond the limits of Kansas, thereby changing the direction of Crooked Creek into the present channel below Wilburn, the general physiographic conditions could easily be accounted for.

Again (p. 27), referring to certain anomalous irregularities in the Red Beds floor, he says:

> The character of the upper surface of the Red Beds is interesting on account of the great irregularities which it presents. * * * Aside from this rapid inclination southward there are other local irregularities. In the Cimarron Valley, where the whole surface is covered by a layer of the soil and silt from 10 to 15 feet deep on an average, occasional places have been found in well drilling where great depressions exist. At one farm house, on the land of Colonel Perry, a well was sunk to the unusual depth of 175 feet without reaching the Red Beds, while less than a half mile away they are exposed almost at the surface. Such irregularities are probably due to surface erosion in pre-Tertiary time.

Professor Haworth is here speaking of the large depressed area within the breaks (the Englewood Basin), which the present writer referred to above as apparently similar in origin to the Meade Basin, only obsolescent. Elsewhere, in describing the Cimarron Valley, he says of this basin (p. 21):

> The valley of the Cimarron rarely exceeds 2 miles in width throughout its course across the Meade quadrangle, but it has scarcely passed beyond these limits when it suddenly widens to an unusual extent. Beginning a few miles above Englewood it has a valley more than 5 miles wide. North of Englewood is a valley, or an area which seems to be a valley of erosion, 10 or 12 miles wide. * * * Such a wide valley appearing so suddenly along the course of a stream is very interesting, as its origin is hard to determine.

Disregarding an irregular grouping of sand hills which form a partially separating ridge only, the two flat areas may properly be regarded as one. The Cimarron wanders along its southern border. A short distance above, this stream is in a canyon, eroding its bed; and below, it runs in a canyon, eroding again; but within the basin it meanders, temporarily at baselevel.

Professor Haworth gives no consideration to the possibility of

A SINK-HOLE CONNECTION WITH UNDERGROUND DRAINAGE SYSTEM

B. UNDERGROUND CHANNEL

origin by faulting here. The west wall of the Meade depression and the east wall of the Odee depression, falling approximately in line, lend some degree of plausibility to his suggestion in the case of those two basins. The difficult assumption has to be made, however, that the two tilted blocks are in the one case tilted away from the fault, and in the other toward it. Furthermore, in the case of the Meade Basin the assumption of faulting would seem to be called for in explanation of west and east walls alike.

Professor Haworth gives but slight consideration to the possibility of origin of such basin-form valleys in widespread caving and settlement of the Red Beds, resulting from removal in solution of their included deposits of gypsum and salt. He notes (pp. 28, 29) the wide occurrence of such included deposits:

> It [gypsum] seems to be well stratified in the vicinity of Medicine Lodge, forming heavy layers from 5 to 10 feet in thickness. These strata have a lateral extent of many miles, and have been important agents in the production of the peculiar and varied physiography for which portions of Barber and Comanche counties are noted. * * *
>
> Salt is also scattered irregularly through the Red Beds. It is leached out by the water and is deposited along the salt marshes, so common in the Cimarron River Valley to the south of the State line [where the Red Beds have been extensively uncovered by erosion]. Probably the salt is irregularly disseminated throughout the material; possibly heavy deposits of rock salt may yet be found beneath the surface, although no positive indication of such has yet been observed. * * * The origin of the Red Beds is pretty well indicated by their character. The large amount of iron oxide, of gypsum, and of salt which they contain * * * imply that they are the result of the accumulation of sediment in a concentrated ocean water. * * * The large deposits of rock salt in what has heretofore been called the Upper Permian—the salt beds supplying the mines at Hutchinson, Lyons, and other places in the south-central part of Kansas—have probably been formed by the desiccation of an inland ocean.

On the other hand, as will be seen from the foregoing quotations, he is inclined to ascribe the Englewood Basin to erosion, adding, however, that its origin is hard to determine. Almost everywhere in the surrounding hills, though sometimes under cappings of Tertiary, the Red Beds are in evidence, indicating that if this is a basin of erosion, the Tertiary in all likelihood has been wholly removed and a considerable depth of excavation accomplished in the bed rock as well. The bed rock (Red Beds) should constitute the floor, except for a light mantling of recent stream alluvium. But on the contrary, Professor Haworth finds, coincident in position with this topographic anomaly, an unusual depth of loose material and a "great depression" of the bed-rock floor. This basining of the buried Red Beds surface he attributes in turn to pre-Tertiary erosion.

On the assumption of settlement by caving within the floor, coincidence of the two depressions is to be expected; furthermore, multiplication of such occurrences does not add to the difficulty of

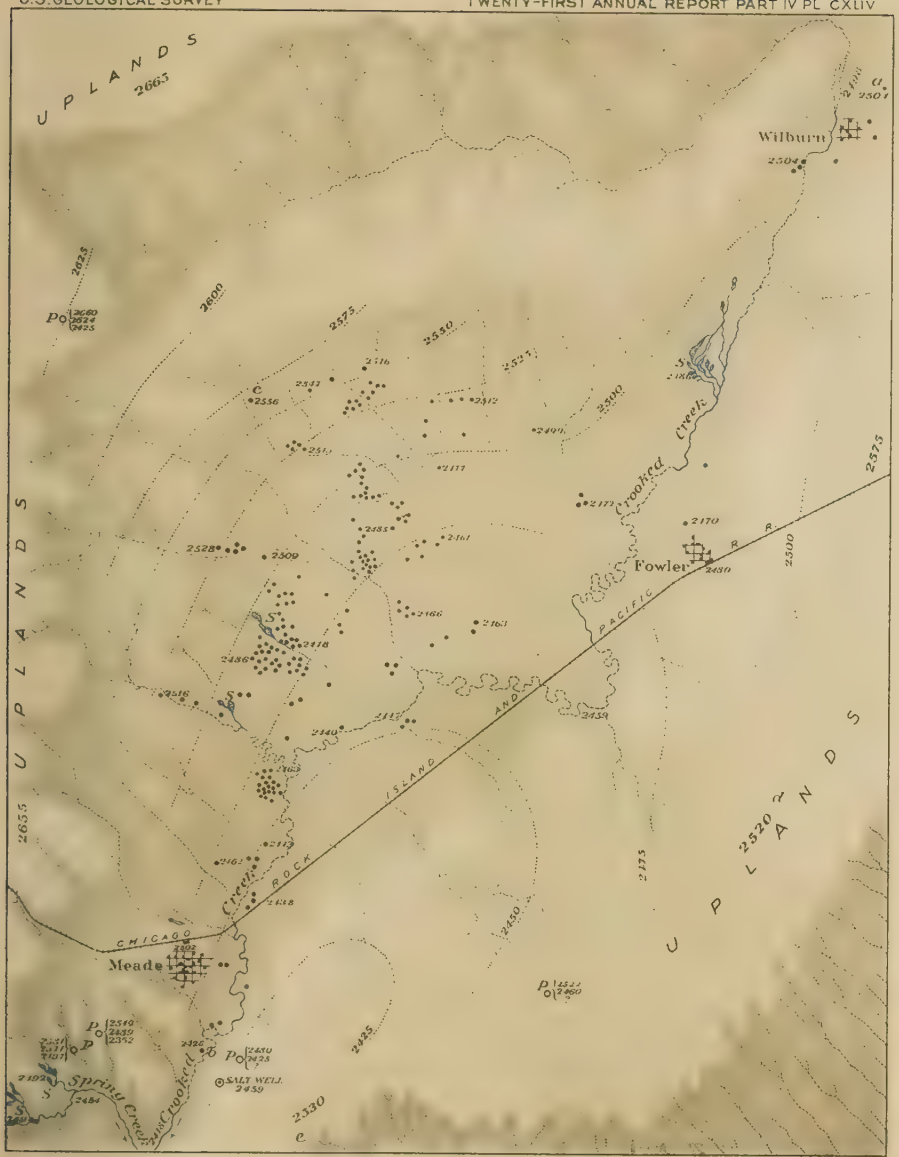
their explanation. A "fry-pan" valley of erosion is an exceptional topographic form. It reflects an exceptional structure in the material acted upon. Such a structure may have been locally present in the Red Beds, accounting for the depression in the underlying rocks, though these show no fry-pan valleys where exposed to the southeast, but in the Tertiary it is certainly not present to such extent as to account for the exact superposition here of the surface basin.

The surface basins in this region—extending through great range in size and in degree of definition—are in fact numerous. The headwaters of Bluff Creek originate in one upon the uplands, just back of the line of breaks, from which escape is made in a sharp canyon. The town of Ashland, 16 miles northeast of Englewood, lies in another, at the foot of the breaks. Seemingly no line of drainage of any considerable length, anywhere within many miles, has had normal development, undisturbed by ground settlement. While the great majority of the appearances suggestive of settlement are not absolutely convincing, yet unmistakable evidences here and there are presented, as for example, on a small scale, St. Jacob's Well, the Salt Well, and certain "basins" referred to as having surrounding sod cracks, and on a moderately large scale, the Big Basin. The fact once established, in even a single instance, of Tertiary settlement resulting from caving in the Red Beds, with their widely distributed soluble deposits, widely distributed basining of the Tertiary surface, wherever the Red Beds lie close beneath, becomes intelligible.

On this hypothesis, the Meade Basin, with all its minor detail of configuration, its present tilted position, the general lowering of levels and diverse tiltings in the near neighborhood, as well as the manifestations of head in the ground water over the whole area thus affected, becomes intelligible also.

As in the case of the Englewood Basin, there is indication in the Meade area of corresponding depression of the Red Beds surface. Wells there have attained a depth of nearly 300 feet, wholly in sand, gravel, and clay, and without reaching bed rock. This depth corresponds to an elevation above sea level of about 2,150 feet. At the Salt Well, on the southern border of the basin, the Red Beds were encountered at a depth of 292 feet, or at an elevation above sea of 2,167 feet. Ten miles below Meade the red formation is exposed on the creek at 2,325 feet. The creek bed at its point of exit from the Meade Basin is 95 feet higher; but the buried Red Beds there, at an elevation of 2,167 feet above sea, have a lower position by 158 feet. That is, in the 10 miles southward, while the eroded surface of the Tertiary declines 95 feet, the Red Beds, from a depth of 253 feet, rise 158 feet to meet it.

Neither the west side of the Meade Basin nor the east side of the Odee Basin, in the course of the supposed "single fault line extending



W. D. Johnson, del. Well positions and levels by D.D. Daly

THE MEADE ARTESIAN BASIN

Scale of miles

0 1 2 3 4 5

Flowing wells (•) Pumping wells (Po) Artesian springs (S)

Figures indicate elevations above sea level. Larger figures, on uplands, approximate. Bracketed figures at pumping wells indicate, first, ground level; second, level in well to which artesian water rises; third, level at which artesian water was encountered. Figures on dotted contours indicate assumed elevations of hydraulic grade plane.

southward to beyond the limits of Kansas," presents a cliff-like escarpment. The margin of the deeply incised and older Odee Basin is much the more abrupt of the two. On the assumption of dulling and recession of an original escarpment by erosion, the fresher Meade Basin should exhibit a difference the other way. Actual faulting is in evidence at several points about the borders of the Yellow House Basin, in the interior of the Staked Plains. This depressed area is closed, and the faulted sections of its rim are arc-form. Their exposures, as well as the records of borings in the basin floor, indicate that rather strongly cemented mortar beds here are both numerous and of unusual thickness. Even assuming origin in general settlement, due to caving within the floor, a sharply localized marginal effect might reasonably be looked for in this stiffened alluvial material. The fault, as a topographic feature, does not appear at Meade, and here arroyo exposures and well records indicate a relatively feeble development of the mortar beds. Faulting, whether profound or superficial, might be expected to operate against the production of artesian pressure certainly not directly to favor it; and in the Yellow House Basin, though its floor is much below the general water-plane level of the surrounding uplands, there is only very feeble flow at the surface, and then only at one end, away from the faulted escarpments. On the other hand, springs occur, as might be expected, at the escarpment foot. The ranch houses appearing in the illustration (p. 728) are located along a line of such springs. The fact that there are flowing wells in large number in the Meade Basin may, indeed, be taken as evidence that there has been no serious rupturing of the impervious sheets.[1]

Probably not one-third of the total area of the valley floor, or not more than 10,000 acres, has flowing wells. Prospecting for water has been thorough, and the areas of possible flow, as shown on the map, are outlined with a fair degree of accuracy by the actual distribution of wells. As already stated, the hydraulic grade plane barely skims the basin floor, slightly underrunning its undulations between minor basins. The possible irrigable area is somewhat larger than the total of these areas of flow, since the wells have rise above the surface and grades are light. In few wells, however, is this rise more than 15 feet. On the other hand, the small basin bottoms, in which rainwater lingers and dries away periodically, do not respond profitably to cultivation. The maximum area possible of reclamation, from this point of view,

[1] In the summer of 1896, several months previous to the beginning of the somewhat detailed study of the artesian phenomena and physiography of the Meade region, which was to be preliminary to the general examination of the High Plains, the writer spent two days at Meade with Professor Haworth, who at that time was engaged in his investigation of the underground waters of southwestern Kansas. The Meade Basin, Spring Creek, and Crooked Creek, down to the outcropping of the Red Beds, were visited in his company, and the writer had, in advance of any definite impressions of his own, the benefit of Professor Haworth's, views, substantially as presented in the report quoted from above. Professor Haworth not only stated his hypothesis of faulting, but gave it as his conviction that the artesian manifestations were the result of local depression of the ground water of the Tertiary, due, apparently, however, to the dropping of a faulted block.

therefore, may safely be placed at 10,000 acres. The area actually irrigated in 1897 was but a fraction of this amount.

Of the 209 flowing wells shown on the map, only about 180 have flow sufficient in amount to be of appreciable value. The delivery in individual cases ranges up to about 50 gallons a minute. A fair average yield among the 180 serviceable wells would be 10 gallons a minute, giving a total yield of 4 second-feet. Making the liberal estimate that half of the yield throughout the entire year could be stored and delivered as needed, only about 1,500 acres each year could be supplied with 12 inches of water.

By multiplying wells at points where delivery is strongest, the total yield might in some measure be increased. It is questionable, however, whether it could be largely increased. Grouping has already been carried so far that further additions to groups would result in perceptible reduction of the average delivery per well. Tests were made to determine this question so far as possible. One of these tests was as follows: In a small isolated group of three strong wells, lying equidistant from one another, about 100 yards apart, and each having a depth of about 160 feet, one was brought to a stand in a pipe continuing the well tube upward. The height reached above the ground surface was 11 feet 4 inches. The two other wells were then plugged. The water level in the standpipe rose slowly. In ten minutes it had ascended 5 inches; in 30 minutes, 9 inches, and in something less than an hour it again became stationary at 15½ inches. After another hour the two plugged wells were allowed to resume their flow. The level in the standpipe then sank, at about the same rate it had risen, to its original level. The experiment was repeated later with only one well plugged, and the rise was nearly 9 inches. Thus, in the case of this single isolated well, the addition of another close by resulted in the reduction of its original efficiency by 6 per cent. From general inspection and the universal testimony of well makers, it became clear that the total yield in the basin at least can not be so greatly increased as to serve the 10,000 acres given above as the maximum area of available lands. It would seem, indeed, that it can not be increased by so much as 50 per cent. That is, the probable limit of yield is within 6 second-feet. The actual yield is about 4 second-feet. The combined flow of the several artesian springs at the head of Spring Creek, already referred to, is a little in excess of 4 second-feet.

The explanation of this low maximum delivery is involved, apparently, in that of the hollowing of the hydraulic grade plane shown by the dotted contours. The ground water beneath the uplands on the west is the source of supply, and under ideal conditions it would seem yield should be conditional only upon the ability of this supply to sustain it. But a hollowing of the grade plane coincident with the topographic depression indicates that ideal conditions do not obtain. The

A

B

ARTESIAN WELLS OF MEADE BASIN.

grade plane should have fairly uniform inclination, modified only by the varying resistance of the ground material, and this variation will be too rapid for broadly extended effects.

Local hollowing must result from local leakage. The impervious cover is at best only relatively impervious. Clay beds beneath the upper level of saturation of the ordinary ground water are saturated equally with the beds of coarse material. A boring extended to the free water plane will encounter it at virtually the same level whether in clay or in gravel. Delivery from clay is comparatively very slow. A boring penetrating to a considerable depth below the water plane wholly in clay may readily be pumped dry. It will then slowly fill again to the original level. But if it be extended farther, to some underlying bed of gravel, and kept dry during extension, strong inflow will be encountered from the gravel bed. This inflow will have upward pressure equal to the weight of a column of water reaching to the water plane, and its rise will be of the nature of artesian rise. In the absence of the well opening there is no upward pressure against the clay, because the latter is itself saturated up to the water plane. If, now, the clay bed could all at once be exhausted of its contained water, it would constitute an artesian cover. However, because it is not absolutely impermeable, it would be a leaking cover. Therefore, it would in time be refilled and the original water plane would be reestablished.

In the case of the Meade Basin the cover is of this character, depression of the whole mass having left the original level of equilibrium above the ground surface. It is slowly permeable. It is therefore a leaking cover. The ground water, however, is not extended above it to a reestablished water plane, because there is drainage off of this leakage. The clay sheet—or connected grouping of clay masses—is in general more or less deeply buried. It leaks into overlying sands and gravels of considerable thickness; and because the basin is tilted, presumably there is drainage off through these overlying porous beds at the lowest point in the rim of the basined clay sheet.

If the clay-sheet basin at its rim rose sufficiently high on all sides, the water of upward leakage would accumulate to the level of the upland water plane extended, as shown in fig. 318 (p. 718). The clay sheet would not then be subjected to upward pressure and would not constitute an artesian cover. The actual hydraulic grade plane is hollowed above the sunken area, and falls below the theoretical water-plane level as shown, because, in the first place, the basined clay sheet beneath is not strictly impermeable, and furthermore, because the water which leaks upward does not accumulate there, but finds passage off southward, through the sunken and eroded areas in that direction, at a steeper grade than the general eastward inclination of the ground water.

The condition may be likened to that of a pipe lying in an open

trench, carrying water under light head, but sustaining loss at imperfect joints, the escaping water forming a stream submerging the pipe. A vertical tube set in the pipe will then show rise to a stand at some height above the water level in the trench. This rise will be less than if there had been no loss from leakage, but on the other hand it will reach higher than any level the water in the trench can assume (unless ponded), however slow its movement.

As we have seen, the flow of wells in the Meade Basin is much more feeble than might theoretically be expected, and this it appears is so because the deep-lying clay beds serve but imperfectly as an artesian cover, permitting upward leakage of water into overlying porous beds, where to a considerable depth it accumulates, though at the same time it drains away. In consequence, above the cover in this porous mass there is a local ground water, having inclination and movement southward. Though surface inflow to the basin may at times contribute to it appreciably, its derivation in the main, unlike the ground water of the uplands, is from below.

As with the water in the ditch, the depth of accumulation, because of drainage off, is not sufficient to balance the upward pressure of the confined water beneath the clay floor, or artesian cover, and when a way is opened for it the latter rises through the overlying accumulation, as the water in the pipe rises through the vertical tube, to some level above the stream in the ditch.

Since it is not to be assumed that the buried cover is a uniform sheet of clay, everywhere permeable in equal degree, this local ground water should have a correspondingly uneven water plane. The so-called surface water is in fact encountered at depths so uneven as to indicate marked undulation. And this undulation shows no relation to that of the basin floor. At several points upon the floor there are small marshy tracts indicating intersection of the two surfaces, yet none of these coincide in position with the minor basins; they occur rather upon slopes. At other points, marked S on the map, there are actual springs. As might be expected, these occur where borings disclose the strongest pressures. They may properly be termed "artesian springs," since their source of supply is not to one side and above, but deep seated and vertically beneath. They rise through the basin ground water and in some cases issue upon the virtually level basin floor. Adjoining wells penetrate to depths exceeding 100 feet—sometimes even to 250 feet—before encountering artesian pressures.

Generally speaking, in the marginal region of the High Plains, wherever the Red Beds constitute the floor, or where their covering of Cretaceous has been greatly thinned, there will be characteristically a zone of gently descending uneven slopes, separating the undisturbed upland from the erosion escarpment or line of breaks. Incidentally, within this zone, there may occur basins of sharply localized settle-

A

B.

ESCARPMENT OF YELLOW HOUSE BASIN

ment. But the zone, as a whole, will be one of settlement, its profiles retaining in the main the original surface. Wherever extensive interbedded clay sheets occur, depressing the water plane below the inclination it would normally assume, artesian pressures will be developed, and the pumping lift in wells may be found to be materially reduced from that upon the uplands. This reduction of lift may, in some cases, approximate to the depth of surface lowering.

The margin of the Cretaceous swings off southwestward from the Meade region in Kansas. The Beaver River in western Oklahoma has cut down deeply into the Red Beds, but the Cretaceous is exposed here and there along its valley slopes on either hand, showing deep Tertiary above and the Red Beds beneath. Upon the "North Plains," between the Beaver and the Canadian, in northern Texas, the Cretaceous at one point even rises to the upland surface, plantation there having brought it into conformity with the general upland level. Along the Canadian it reappears, sometimes thick, sometimes thin, and again altogether absent. The Tertiary, in short, has marked variation in depth, though its upper surface is virtually a plain. The floor upon which it rests, deeply and variously eroded, is in the main, perhaps, of Cretaceous rocks, but along the deeper pre-Tertiary valleys these rocks have doubtless been widely removed. Apparently this is the condition beneath the great plateau of the Staked Plains, as indicated along the canyon walls of the Paladuro and other deeply incised spring streams, which head back some distance within the eastern plateau front. The large basins occurring in linear arrangement, as well as the wide trough-like depressions, sections of which are occupied and accentuated by lines of drainage, have already been referred to. Furthermore, in contrast with the flatness of the plateau in general, much broader areas exhibit diverse and faint but far-reaching grades, which are hardly to be accounted for except on the assumption of uneven regional settlement. Thus artesian manifestations from the ground water may reasonably be looked

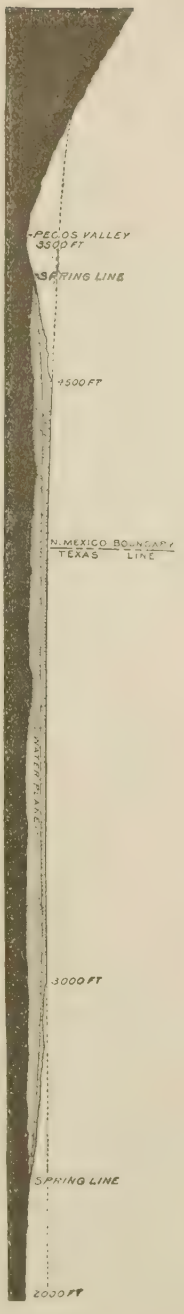


Fig. 319.—West-east section of Staked Plains plateau, showing ground-water level above that of limiting river valleys.

for in the interior of the plateau areas, as well as along the marginal region, as at Meade.

It was the writer's expectation at the outset of this investigation that it would be found to be possible to duplicate the results at Meade in many of the large interior basins. It appears, however, that conditions at Meade were exceptionally favorable. The depth to water in that region is comparatively slight. It is but 50 feet on the uplands to the west of the Meade Basin. Upon the uplands generally it is much greater than this. The depth varies slowly, but it ranges down to 150 feet and more. Probably the mean is little short of 100 feet.

In order that there may be flow at the surface, therefore, and not rise in wells part way merely, the basin floors must have these considerable depths below the general level; at the same time there must be unbroken extension of impervious beds beneath. As a rule the basins are not deep enough. As a rule, also, the requisite underlying clay sheet, of greater extent than the basin, is not present. Commonly the water plane is encountered, at some slight depth, at a level continuous with that beneath the surrounding uplands. There is marked advantage in this, owing to the great reduction of the pumping lift, and the gain here is but slightly offset by diminution of power to windmills, since the depth of a basin is slight relatively to horizontal extent; but in no other instance has the writer found that the water-plane level extends high above the basin floor. The Yellow House Basin and a few others already mentioned have flow at the surface over fractional areas of their bottoms, though in no case in sufficient volume for important irrigation. That it may not be materially increased appears from the fact that in each instance the water plane beneath the uplands near by is barely above its level.

In one particular the Yellow House depression presents an interesting exception to the general rule. As at Meade, the floor is not level, but sensibly hollowed. The artesian patch lies at one side of the center on a faint grade. There is, in consequence, a central area a mile or more in diameter which has a lower position by several feet than the upland water plane.

It would seem, therefore, that the ground water here should be exposed, forming a broad and shallow lake, as, in the case of the small basin near Englewood it forms a relatively deep pond (Pl. CXXXII). There is instead a marsh of somewhat less dimensions, with open water in pools. In winter the pools enlarge; in summer they become smaller or may even wholly disappear. There is a considerable upland area which the backward cutting of storm drainage has made tributary to the basin, and after heavy rains a flood-water lake is created; but this soon dries away. Apparently it is by evaporation, also, that a ground-water lake is kept down. The factors here are the rate of evaporation on the one hand, and on the other

A.

B

ARTESIAN SPRINGS

the rate at which the ground material is permeable to the upward rise of water under the light head which evaporation creates. In wells at the marsh border water stands flush with the surface and borings give sections of uniformly fine material, so far as they have gone. Hence, at all points within the marshy area water rises as readily as it is contributed to these wells. No borings have penetrated to the floor. It is, therefore, not unlikely that open-textured material exists beneath. Some distance back from the marsh, far enough to secure an intervening belt of irrigable land on the faint slope, it would seem that it might be worth while to put down a test boring. The belt could have but little breadth at best, for it is limited between the two planes of the hypothetical lake-level and the actual evaporation level of the marsh, and with retreat upgrade the possible artesian rise above the ground surface would correspondingly diminish. It happens, however, that the marsh is strongly saline—a result in this case, apparently, of long accumulation of the evaporated residue from surface waters—and ponding after rains annually spreads a salt deposit to a broadly expanded shore line.

As we have seen in the case of the Meade Basin, such artesian covers as the complex structure of the Tertiary may afford are only relatively impervious, and operate as such only when there is opportunity for the inevitable upward leakage to drain away. At Meade there is drainage through overlying porous beds, because the basin is at the edge of the uplands, where the water plane dips strongly, intersecting its floor. An interior basin, though provided with a continuous clay sheet and lying below the nearly level water plane, must reproduce the latter as a lake surface—except for the slight amount that evaporation will lower it. It will not matter that the rate of upward passage through the clay sheet is gradual. The clay sheet can be effective as an artesian cover only where there is drainage off through overlying porous beds at some rate more rapid.

It is therefore apparent that the utmost that can be looked for in the way of artesian possibilities within the large depressions of the High Plains is the occurrence occasionally—not always—of a small tract on the slope of a hollowed basin floor which will afford flow sufficient merely for the irrigation of a garden patch, determining the location of a ranch headquarters or a watering place for stock. More promising, however, than the inclosed basins are the long, flat slopes, products of settlement also, which occasionally intervene between the erosion front and the uplands proper, or which sometimes for considerable distances border the valleys of the larger transecting streams, such as the Canadian.

These tilted marginal tracts of the old plain often have steeper inclination than the dipping water plane beneath, and where the requisite clay sheet is present and there are erosion channels lowering the

ground surface locally there is opportunity for flowing wells. Here occur the numerous small perennial streams, having origin in springs which may properly be termed artesian, which from the beginning of the stock-growing industry have been utilized for ranch sites. Their number may be notably increased above the natural "spring line" by artificial outlet for the imprisoned waters.

THE GROUND WATER.

All the materials of the earth's crust—the hard rocks in great variety and their loose covering of disintegration products alike—are permeable to water; and virtually the whole is saturated with water. There is even an excess over saturation, as indicated by the oceans.

Except for crustal unevenness, which leaves it ponded in confluent basins, this excess would form a continuous ocean envelope. Wherever it does extend, however, the ocean surface conforms very nearly to the ideal spheroidal figure of the earth; and that figure would in effect be completed, by continuation of the ocean level as a level of saturation, or universal water plane, beneath all continental and island masses, if it were not for the endless round of evaporation and precipitation by which water is continually lifted from ocean surfaces to be showered upon land surfaces. This water of precipitation in large part runs off again to the sea; a part also is evaporated, either directly or out of the soil; yet some portion penetrates downward beyond recall. Thereby the saturation surface everywhere is built up virtually to the land surface.

But ground water is not permanently stored. Its level tends continually to sink. There is drainage off along faint grades to the sea, and at rates varying as greatly as the permeability of the various rock materials and their loose covering varies. The mean rate of this movement, however, is exceedingly slow. It is much slower than the mean rate of replenishment from precipitation. Underground loss can exceed the precipitation supply only on grades that for surface run-off would be steep; and all land masses, excepting small mountainous islands, have such broad extent relatively to elevation above sea that, topographic irregularities of the surface aside, their grades are faint.

Thus, with the rate of filling notably greater than the rate of loss, greater even under the average of desert conditions, the saturation surface would coincide with the land surface if it were not for topographic irregularity, which affords steep grades locally. In consequence, the water plane beneath a mountain mass may lie at a considerable depth, though even then it will be domed above its general level, or on a slope it may pass out at the surface, marked by a spring line; or across a hollow it may have representation, approximately, in the surface of a lake. That is, locally it may lie at a considerable depth below ground, with compensation by escape elsewhere.

A. SAND-HILL TRACT.

B A SAND HILL

A. "DRY FARMING"

B. A "TANK."

Streams in their flood flow represent the run-off from precipitation direct; but essentially it is from the ground water seeking to adjust diverse grades to a mean grade of equilibrium that streams in their normal perennial flow are sustained. Perennial streams, strictly so called, lie below the water plane; intermittent streams, above. Even in humid lands the branchings of a system of drainage at relatively high grades are intermittent—have flood flow only. In this

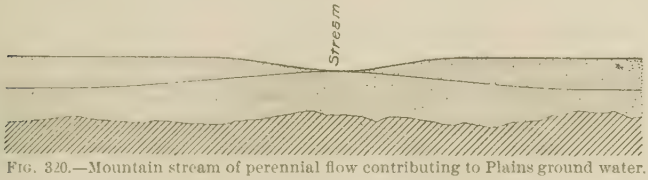


FIG. 320.—Mountain stream of perennial flow contributing to Plains ground water.

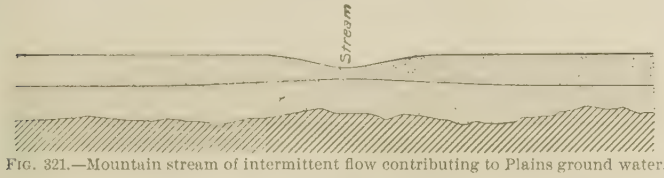


FIG. 321.—Mountain stream of intermittent flow contributing to Plains ground water.

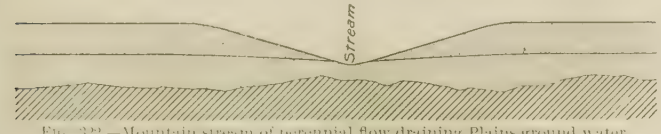


FIG. 322.—Mountain stream of perennial flow draining Plains ground water.

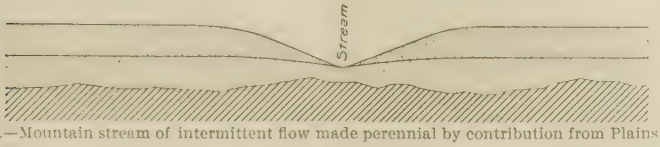


FIG. 323.—Mountain stream of intermittent flow made perennial by contribution from Plains ground water.

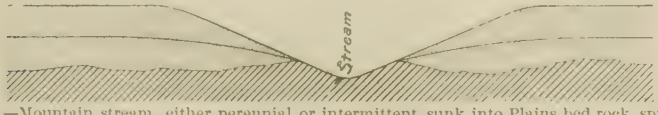


FIG. 324.—Mountain stream, either perennial or intermittent, sunk into Plains bed rock, spring-fed along base of Tertiary.

zone above the plane of ground-water equilibrium the whole surface may be regarded as covered with them. Below is the zone of ground-water escape. But as the permeability of ground materials is very widely variable, escape will take the form of springs, heading streams, or contributing to their flow from beneath; and as clear running water cuts channels, the slowly permeable interstream areas will be drained down approximately to stream level, as a marsh is drained by ditch-

ing. Thus there is an upper zone in which normally dry stream beds everywhere lie above the ground water, though in flood they in a measure contribute to it, and another in which the ground water extends its surface sensibly above the streams, maintaining them in perennial flow after the surface contribution has passed. Toward the close of a protracted period of drought the spring sources of perennial flow become largely revealed. The perennial streams, then, in their upper reaches at least, are the measure and indicate the importance of the ground-water contribution to run-off.

But while the regions of higher elevation everywhere are the zones of intermittent flow, in arid lands the saturation surface underlies usually at a considerable depth the areas of low elevation as well. There are normally no perennial streams. Spring flow may for short distances occur in canyons at the sharp change of slope at the foot of a desert range. Or, under exceptional conditions, such as obtain at

FIG. 325.—Map of valley floor subject to floods, showing sand-wash belt and subdividing stream.

present upon the Plains, the intermittent drainage from a range may be reversed from the aggrading to the degrading habit, and, sunk in valleys to the desert ground water, be sustained thereby between the infrequent rains. But normally in arid lands the water plane everywhere underruns the ground surface, and after floods drainage lines quickly resume their characteristic aspect of dry stream beds—not because the flood water has passed on to the sea as in humid lands, but because it has been extended upon unsaturated ground and become absorbed.

The fact that under normal conditions the water plane in desert lowland regions of seaward inclination nowhere intersects the surface, but, on the contrary, is almost universally low lying, is not to be attributed to the relatively light precipitation. The explanation is to be looked for in the deep burial of bed rock under open-textured material, which affords opportunity for relatively rapid drainage. At

DEEP-WELL STOCK-WATERING PLANTS ON UPLANDS

A

B

DEEP-WELL MAKING ON UPLANDS.

the same time in deserts, as regions of aggradation, the tendency is away from topographic diversity toward uniformity of grade. Thus the ground-water surface has the impressive character of a vastly extended plane.

In humid lands, as a rule, the depth through loose ground to bed rock is slight. Occasionally even the rock is exposed at the surface or lies so thinly covered that it may readily be reached for building foundations. This is not true of base-level plains along coasts and rivers, but these are subordinate features; humid lands are primarily regions of degradation, and the covering of bed rock is, as a rule, shallow and discontinuous. In deserts, on the other hand, the tracts undergoing degradation are essentially islands of bare rock merely, rising amid far-reaching accumulations of their own waste products. On the desert plains, built and spread out by these accumulations, the depth of burial of the bed-rock floor is comparatively great. It is

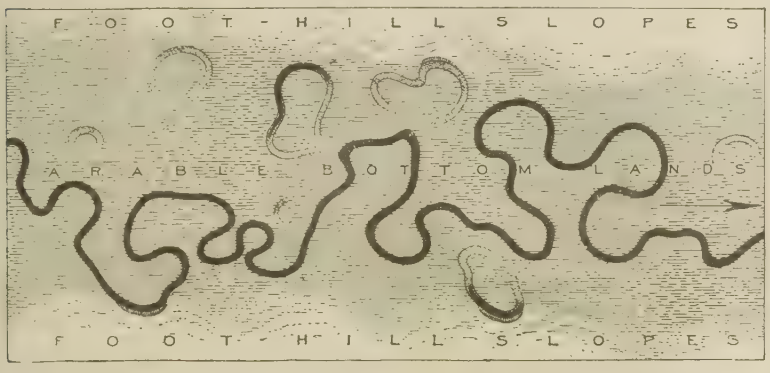


FIG. 326.—Map of valley floor not subject to floods, showing intricately meandering stream.

variable; for, while the ground surface does not have the diversified relief characteristic of humid lands, the buried bed-rock surface will usually be uneven; nevertheless, in deserts this covering of loose material is relatively continuous and deep. At the same time, it is true, the depth to the water plane is notably greater than in humid lands. As a rule, however, the depth to water is but a small part of the total depth in water to the floor.

Commonly it is in loose material only that ground water delivers to wells freely. The fact of its occurrence in sound, unfissured rock (below the universal water plane) is not appreciable to the well user. The "voids" which are present even in fine-grained rock may be completely filled—that is, the rock may be saturated—and yet the rate of escape into a well opening under the head created by the depth of well excavation below the water plane will be inappreciably slow. A block of building stone, for example, removed to the open air from

below the water plane, or "water table" as it is styled in quarries, may take days or months to dry out. On the other hand, and at the other extreme, open-textured sandstone may have about equal permeability to that of clay beds in unconsolidated material. But while, generally speaking, the actual saturation content per unit of mass of consolidated and unconsolidated material does not greatly differ, there is such very marked difference in their rates of delivery that in matters of water supply, as a rule, it is only loose ground that may be said to be "water-bearing" at all. Since all materials of the earth's crust have this nearly equal capacity for water, the more accurate expression would be "water yielding;" yet as the rates of permeability, or, what is the same thing, the rates of delivery under pressure, diminish at a rapidly increasing ratio with diminution of the openings between grains, a well in bed rock if the rock be unfissured is virtually non-yielding. Ground water seemingly ends where loose ground comes to a bottom on solid rock. Within such limits it is the water of the common well.

It is generally recognized only in a vague way that loose ground can not be in a condition of saturation, or at least does not permanently remain so, unless the underlying rocks also are saturated. Especially there is no general recognition of a single water plane, continuous through all materials, though undulated in response to widely varying rates of drainage movement, and below which all materials are saturated to indefinite depths. A sharp distinction is made, where essentially there is none, between the water in loose ground and so-called "underground waters." This distinction originates in humid regions of extensive degradation, where the loose covering of bed rock is characteristically thin and discontinuous and where in consequence the contained water has but shallow depth to its floor. The water of the common well in such regions is looked upon as a surface accumulation merely, since often it lies virtually pocketed in basins of the bed rock and may be materially reduced in volume by heavy pumping. The water plane in humid lands, it is true, is usually to be encountered close to the surface, so that a well rarely fails of some yield, but it is only under exceptional conditions there that a water supply in large volume is to be had from the ground water.

Though saturation continues indefinitely downward, it is only under exceptional conditions also that the presence of water in bed rock becomes apparent. It is found standing free, in fissures, or draining off, as streams, through solution passageways, to which fissures may become enlarged where they occur in easily soluble rocks, such as limestone. In the one case, minutely fissured rock may have a delivery, under the light head which the ordinary well excavation affords, fairly approximating that of unconsolidated material; and underground drainage, through solution passageways, may have the

A. CANADIAN RIVER IN NORMAL FLOW.

B. CANADIAN VALLEY AFTER HEAVY FLOOD.

A.

B.

BEAVER RIVER IN FLOOD.

volume of considerable streams. Again, a broadly continuous and undisturbed bed of open-textured rock, such as coarse sandstone, covered in turn by some close-textured rock, may give striking evidence of the presence of water by the instant filling, or even the overflow, of a well opening reaching down to it. Such vigorous yield is termed "artesian;" and this deep-seated water will come to rest at a water-plane level of its own; nevertheless, the water in the artesian bed and that in its cover are of the same body. The rates of its yielding to pressure merely, in the open-textured and in the close-textured materials, are very widely different. The water plane, as noted, is not an evenly domed surface over land areas, but is locally either hollowed or mounded, because of varying resistance to the general ground-water movement seaward; and the relatively free-moving water of the "artesian" bed seeks instantly to attain, through the well opening, the level it would have had if all beds had been of equal permeability. It does so under the impulse of a "head" pressure vastly greater than that afforded by pumping in the ordinary well in loose ground.

Delivery, or "flow," from the ordinary well results from the lowering, as a rule, by only a foot or so, of its standing-water level—that is, the general water-plane level extended across it. Flow is set up from the relatively inert water in the ground surrounding, seeking to restore the depressed level. The head, here, inducing flow, is merely the foot or more of lowering. Response to such light impulse is liberal and rapid because the frictional resistance to movement, say in gravelly ground, is immeasurably less than in even the most open textured of solid rocks. Under the same head the deep-lying "artesian" sandstone, from which water literally gushes when it is first reached by an open boring, would appear not to be water bearing at all—just as the close-grained cover through which the boring must pass, though saturated also, is relatively nonbearing as compared with the sandstone. But the sandstone yields freely, like the surface gravel, because of the great depth below the water plane at which an opening is made for it. If a tube, closed at bottom, could be sunk to an equal depth wholly in gravel and then opened, there would be the same high head and heavy upward pressure, but a much more violent uprush in proportion, as the permeability of the material would be greater.

Water encountered in fissures, and conspicuously in the case of deep-lying fissures in generally sound rock, behaves in essentially the same manner as so-called artesian water.

In minutely fractured rock the water plane may be extended much as in loose ground (see fig. 327), but this condition rarely continues to any considerable depth. In a boring penetrating to a system of fairly open fissures, deep below the water plane and in close-textured rock,

there will be instant rise, showing that, relatively, this "underground" water is confined there under pressure. Strictly, the phenomenon is one merely of comparative rates of delivery. The inclosing rock has its interstices filled with water under like pressure; it delivers it to the well opening, however, at an inappreciable rate. Furthermore, the rising water from a fissure usually comes to a stand at a level more or less out of accord with the position which the water plane has locally. As with a deep-lying, far-extended, open-textured sandstone, this level marks a hydraulic grade plane—that of the fissure system. And if, like the artesian bed, there is comparatively free

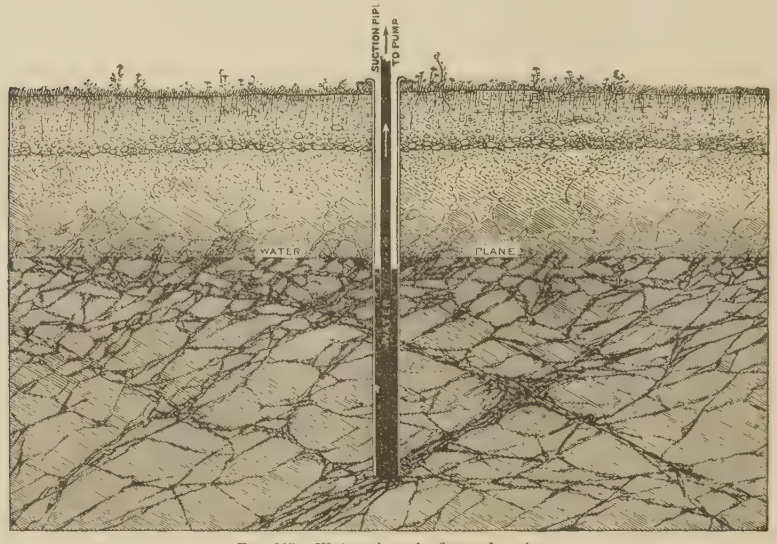


FIG. 327.—Water plane in fissured rock.

surface connection at a distance upgrade, and virtually none in any other direction, this level of equilibrium may lie not only above the normal water plane, but above the ground surface, resulting in voluntary delivery.

A group of tubular wells, one reaching to an artesian bed, another stopping in the relatively impervious rock constituting the artesian cover, and a third opening communication with a system of fissures in such impervious rock, would be likely to show differing, perhaps even widely differing, levels in the region of the water plane. These levels might lie either above or below the water plane, as revealed, for example, in an adjoining "shallow" well wholly in loose ground. Thus artificially brought into contrast, they would present a comparative measure of the differing rates of drainage movement at the several depths to which they penetrated. Those which lay above the

WILD-HAY BOTTOM IN A SPRING-STREAM VALLEY.

IRRIGATION IN CIMARRON VALLEY.

normal water plane would indicate comparatively retarded movement. In the case of an artesian bed, from which, nevertheless, flowing wells are had, the tendency to rise in a boring above the water plane is indication of slower general movement than in loose ground at the surface.

The phenomenon of surface overflow—of the flowing well—is the effect merely of the local accident of topographic configuration by which the ground surface has been given position below the level which the water plane would assume if drainage conditions, affording the same rate of movement as in the artesian bed, continued upward to it without change. While movement within the artesian bed normally is slower than in loose ground at the surface, rapid movement, in a region about the well foot, is set up toward this artificial opening, and there is continuous rise and overflow, owing to the fact that the column of water in the well tube fails to reach a balancing level. The upward

FIG. 328.—Superposed gravel courses.

impulse at the well foot is the equivalent of the weight of that length by which the column falls short of this balancing level—that is, the water in the porous rock in the region immediately surrounding the well at its foot is under hydrostatic pressure equal to that of a column of free, standing water reaching to the hydraulic grade plane. The actual column of water in the well tube exerts an opposing pressure, but less by the amount that it is cut off below the grade plane, or is shorter than the theoretical column. It is only this difference, or the weight of the extra height necessary to bring the artesian column to a stand, that is the effective head operative within the artesian bed beneath, to produce flow at the surface. As hydrostatic pressure, exerted for instance against a cap closing the well at top, it would be the same whether the connection below were with a relatively porous rock sheet or a system of open fissures. It would be the same even if there were connection with another pipe rising to a reservoir at the grade-plane level.

But with the cap removed, the rate of response to pressure in the several cases would be very different. From the fissure system it might closely approximate to that from the assumed pipe rising to a reservoir; from the artesian bed, however, the factor of frictional resistance to the movement thus set up would play so prominent a part that only under high heads could there be any considerable yield at all. Though in a standpipe above the ground surface artesian water might at first rise rapidly because the head was high, the rate of rise would rapidly diminish, and finally, through a number of feet, it would be barely appreciable. It is owing to this fact that in the marginal region of an artesian area there are often so many wells which apparently just overflow, and seem, therefore, to mark the hydraulic grade plane, though among themselves there may be considerable differences of elevation.

Conditions requisite for the development of the high head—i. e., high position of the grade plane above the local water plane, necessary to the production of strong flow from even the most open-textured rock—rarely present themselves. That they are ever present is due

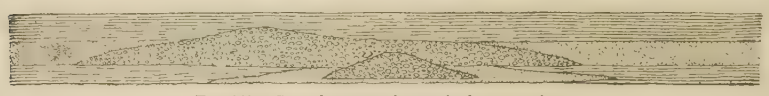


FIG. 329.—Gravel courses in vertical connection.

to the fact that bedded rocks of widely differing degrees of permeability sometimes extend from high areas beneath sloping plains to great distances.

On the other hand, since water from extensive fissures, however deep under ground, will rise in a well opening to its grade plane virtually at a jump, high heads would not be essential to the development of strong flow. But with fissures the grade plane will usually lie below, not only the ground surface, affording no opportunity, therefore, for flowing wells, but below the local water plane also. For where there is fissuring at all, it is usually widely extended, and though these fissures or fracture planes may penetrate deeply, they multiply and open toward the surface rather than downward, thus affording drainage way within bed rock which may be superior to that in the depth of loose ground overlying. A closed system of fissures—that is, one with no opening to the surface—would show a grade plane in a well boring no different from that of its inclosing rock; and one opening at a distant point upgrade only, would show prompt rise to that distant level; but ordinarily the rise of water from fissures in bed-rock falls short of the local water plane, as shown in the comparatively shallow "surface" wells. The deep well of this character, therefore, has the disadvantage of a more or less increased pumping lift. This is a marked characteristic. The disadvantage may

A. HEADQUARTERS CATTLE RANCH ON A SPRING CREEK.

B. A "WATER HOLE."

be compensated, however, by superior freedom of delivery. In other words, because circulation through the fissure system is comparatively unimpeded, a single well will draw promptly from a considerable radius. But as compared with the volume of water in loose ground of a corresponding area above, that in the fissure system is small. By many wells operated together and continuously, its level would be rapidly drawn down to an uneconomical pumping lift. They would somewhat rapidly recover, but under ordinary and continuous pumping, simultaneously, they would nevertheless be rapidly "exhausted." The fact does not become apparent, since fissure openings are encountered only by blind sinking, and rarely.

The yield from an isolated well of this character, therefore, is delusive. The occurrence of such deep-seated water presents striking features. It comes to a standing level independent of that in the loose ground surrounding, seeming to indicate a different source of supply. Its response to pumping is rapid, suggestive of an abundant supply. But especially it rises to its level through an interval of apparently barren rock, and whether from a fissure or a porous sandstone, it begins its rise with force.

It is not recognized by the well user that the apparently barren rock is in fact saturated also, and that, so far as static pressures are concerned, it transmits them undiminished, the differences of the standing-water levels for different materials being due to relief of pressure by drainage off at different rates. It is for this reason, as before stated, that popularly a sharp distinction is made between the water in loose ground covering bed rock and "underground waters." The one is nearly universal, and is regarded as the ground water proper; the other, whether encountered in fissures or in exceptionally porous beds, is seemingly adventitious and unusual, penetrating dry rock masses.

[Owing to unavoidable circumstances this paper could not be finished by its author in time for publication of the whole in this volume. Some of the later plates and figures were intended primarily to illustrate the unwritten portion of the paper; they are here included because they are of general interest in connection with the subject. It is hoped that the author will be able in the near future to write the complementary portion, in accordance with his original plan, for publication in supplemental form.—F. H. N.]

TWENTY-SECOND ANNUAL REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

TO THE

SECRETARY OF THE INTERIOR

1900–1901

CHARLES D. WALCOTT
DIRECTOR

IN FOUR PARTS

PART IV.—HYDROGRAPHY

F. H. NEWELL, CHIEF OF DIVISION

WASHINGTON
GOVERNMENT PRINTING OFFICE
1902

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THE HIGH PLAINS AND THEIR UTILIZATION

BY

WILLARD D. JOHNSON

(Conclusion of paper in Twenty-first Annual Report, Part IV)

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ERRATA.

Corrections of plate numbers should be made as follows:

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For Pl. LVIII, opposite p. 644, read Pl. LIV.
For Pl. LIX, opposite p. 646, read Pl. LV.
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THE HIGH PLAINS AND THEIR UTILIZATION.[a]

By Willard D. Johnson.

RÉSUMÉ OF PRECEDING PAPER.

POSITION, CHARACTER, AND ORIGIN OF THE HIGH PLAINS.

The High Plains constitute a natural subdivision of the Great Plains area, forming a belt extending north and south midway of its slope. The belt is cut across by streams from the distant mountains on the west, in parallel system, wide apart. Its distinctive character is lost, to the northward, in south-central Nebraska. At the southern end, the Staked Plains of Texas constitute the largest individual plateau fragment.

Except for this cross dissection, the belt preserves, untouched by erosion, an original smooth surface once characteristic of the Great Plains as a whole. In a parallel belt or zone to the east, despite the universal sod covering there, the heavy precipitation of a humid climate has lowered the old surface by degradation, and left it, in the main, irregularly undulated. Here are the Prairies. Again, in a zone to the west, in the absence of sod covering (grass growing only in isolated tufts), even the light precipitation of an arid climate has been effective in lowering the old surface, leaving it, however, not undulated, but sharply and minutely cut up. This is the desert zone. The semiarid or subhumid belt of the High Plains lies between.

Thus, by reason of degradation on either side, the High Plains are in relief. Relatively to the horizontal extent of the individual tables the relief is inconsiderable, but is nevertheless emphasized by the striking contrast of these flat surfaces with contiguous uneven surfaces of degradation on the east and west. The High Plains are conspicuously uplands of survival. Yet their mass, to depths often of several hundred feet, is of unconsolidated silt, sand, and gravel. They are plateaus by virtue of their resistance to erosion; yet they are soft plateaus. Their survival has been due to the protective influence of a universal close-knit sod, to which a subhumid precipitation especially has given origin, and yet against which it is unequal, on a grade of 10 feet to a

[a] Being the conclusion of an unfinished paper on the High Plains and their utilization, by Willard D. Johnson, published in Twenty-first Ann. Rept. U. S. Geol. Survey, Part IV, 1899–1900.

mile, to accomplish the first faint beginnings of erosion and the initiation of drainage. There is no run-off. Even heavy local downpours, which in the arid belt, by rapid concentration, would result in local floods and sharp channeling, are here rendered practically inert by the grass mat until disposed of through ground absorption and evaporation. The High Plains, in short, are held by their sod.

The original smooth plain, of which only this transverse belt remains unscarred, was alluvial—i. e., stream-built. It was spread, in substantially its present position as to elevation and inclination, by widely shifting, heavily loaded, and depositing streams from the mountains. Shifting deposition, burial, and plain building constitute the normal habit of desert streams. There is independent evidence that the climate then was more widely arid than now. Virtually the same mountain streams are at present cutting away and degrading where formerly they made broad fan-form deposits and built up. They are running in fixed courses and have excavated valleys.

But relatively humid conditions, with valley cutting, not only followed, they preceded, the period of desert accumulation. An earlier topography of wide, shallow troughs and broad intervening ridges, cut in hard rock, was buried. In consequence, the alluvial covering, spread to a smooth surface, has varying depth to bed rock. Over considerable areas above the old valleys this depth exceeds 300 feet.

The geologic date of its building was late Tertiary. In consequence, the sandy and gravelly mass is sometimes referred to as the "Tertiary gravels." It is believed by many to be lacustrine in origin, the assumption being made of deformation of the Great Plains area, first, lowering it from an inclined position, which it must have had during the early erosion, to a level one, and, finally, after the assumed accumulation of broad lake deposits, restoring it to the present inclination. But the writer regards as unmistakable the evidences of graded construction, by desert-stream deposition, upon substantially the same slope as at present.

Among these evidences are the patchy character, the overlapping and the rapid thinning and thickening of the beds of the finer materials, and the prevailing coarseness and channel-form occurrence of the gravel at all levels. With lake deposits, gravel of any size is a phenomenon only of the shore line, and its distribution there will be in symmetrical lines. In the case of the Plains the sources of derivation having been wholly or at least mainly from the one side—that of the Rocky Mountains—gravel should be disposed in long curving bands, parallel in general to that side. Instead, it occurs unmistakably in irregular west-east courses, and at all depths within the mass. This fact is brought out by comparison, on the one hand, of well sections, where wells are closely grouped, and, on the other, of natural sections, where, at the canyon junctions of spring-stream tributaries with the

A. SAND-HILL TRACT.

B. A SAND HILL.

traversing mountain streams, such sections are presented at right angles. As to the coarseness of the gravel, while individual specimens as large as cobbles are to be found at all depths, even so far out from original sources of supply as the central High Plains region, irregular channel-form beds, often traceable for miles on eastward courses, are made up in large part of egg-size material.

The present valleys as a rule are not cut down to bed rock, though the Canadian Valley is, full length. In some cases unconsolidated material is still deep beneath them. This is the condition in the Arkansas Valley at Garden, Kans. Here and for considerable stretches along the floors of several other streams there remains a notable depth of such material, varying in texture from clay to coarse gravel.

NONIRRIGABLE UPLANDS; IRRIGABLE VALLEYS.

The subhumid precipitation is insufficient for agriculture without irrigation and the only possible agricultural lands of the High Plains belt lie within the valleys, where small patches here and there are irrigable. The most evenly tillable area of the Great Plains lies within the High Plains, yet it is as a body nonagricultural, because a supply of water for irrigation is not obtainable. Upon the uplands proper irrigation on a large scale is impossible, and even where it is possible on a small scale it is economically impracticable. All apparent sources of supply considered, there is not water enough for appreciable effect in general and permanent reclamation, and what small supply there is in fact is not economically available.

The seemingly possible sources of supply are (1) the run-off from the region to the west, either as perennial streams or as flood flow, stored; (2) artesian waters of mountain origin, and (3) the ground water underlying the High Plains themselves.

The streams from the relatively small area in the mountains which has eastward drainage are not great rivers, like those, for example, from the Himalayas, which irrigate the arid plains of India, but their volume is insufficient for the needs even of the desert zone which they have first to cross. Already the Arkansas, which some years ago was extensively diverted for irrigation in the valley bottom at Garden, has become dry there in the crop-growing season, because of large increase of the irrigated area to the westward, in Colorado. To prevent losses incident to long transportation, even with the fullest practicable storage, there will inevitably be further contraction and concentration upon more compact areas nearer to the sources of supply, where available lands are abundant.

As to artesian waters, there is no instance, among many experimental deep borings upon the High Plains, of rise to the upland surface. Furthermore, the total volume of the possible artesian supply, at its source, is relatively insignificant.

THE GROUND WATER.[a]

Ground water at greater or less depth is a universal phenomenon. All the materials of the earth's crust—the hard rocks in great variety and their loose covering of disintegration products alike—are permeable to water; and virtually the whole is saturated with water. There is even an excess over saturation, as indicated by the oceans.

Except for crustal unevenness, which leaves it ponded in confluent basins, this excess would form a continuous ocean envelope. Wherever it does extend, however, the ocean surface conforms very nearly to the ideal spheroidal figure of the earth; and that figure would in effect be completed by continuation of the ocean level as a level of saturation, or universal water plane, beneath all continental and island masses, if it were not for the endless round of evaporation and precipitation by which water is continually lifted from ocean surfaces to be showered upon land surfaces. This water of precipitation in large part runs off again to the sea; a part also is evaporated, either directly or out of the soil; yet some portion penetrates downward to form ground water.

But ground water is not permanently stored. From a definite water plane, or upper level of saturation, it extends indefinitely downward, through practically all of the earth's crust, continually sinking toward sea level—or toward the plane of the sea extended beneath land masses—and continually renewed by ground absorption of some portion of the surface precipitation. Its rate of sinking annually is measured by the depth merely of this fractional part of the annual precipitation. Obviously the downward movement is very slow, much slower than the mean rate of replenishment from precipitation, and at rates varying as greatly as the permeability of the various rock materials and their loose covering varies. But the possibilities of motion are not so great as to admit of appreciable yield to wells under the low heads produced by ordinary pumping. As a rule it is only from loose or unconsolidated material covering "bed rock" that ground water yields appreciably to pumping. To the well maker, therefore, it is only in this cover that ground water occurs at all.

WATER IN HARD AND IN SOFT ROCKS.

A bed of open-textured sandstone may have an actual water content equal, per unit of mass, to that of a gravel bed. Though its interstices are very much smaller, they are correspondingly more numerous. But because they are so much smaller the rate of delivery from the sandstone is so slow as to be imperceptible at ordinary pumping heads.

[a] The first part of this paper, in the Twenty-first Annual Report of the United States Geological Survey, pp. 601–741, closed with an uncompleted discussion of the water resources of the High Plains. Surface waters (the mountain streams) and artesian waters had been considered. The consideration of the third possible source of water supply, the ground water, is now undertaken.

A. "DRY FARMING"

B. A "TANK."

since the frictional resistance to flow increases very rapidly with diminution in the size of openings.

To secure a delivery from the sandstone equal to that from gravel an enormously increased head pressure would be necessary. Such pressures are encountered naturally under so-called artesian conditions, where the influence of a distant very high head is felt in an exceptionally porous rock sheet, extended beneath a relatively impervious sheet. A deep boring, then, opening a way of escape, develops the fact that water may nevertheless be present in hard rock in large volume. Yet the same rock under the pressure of only a few feet created by pumping in the ordinary well would have virtually no delivery and would appear not to be water bearing at all.

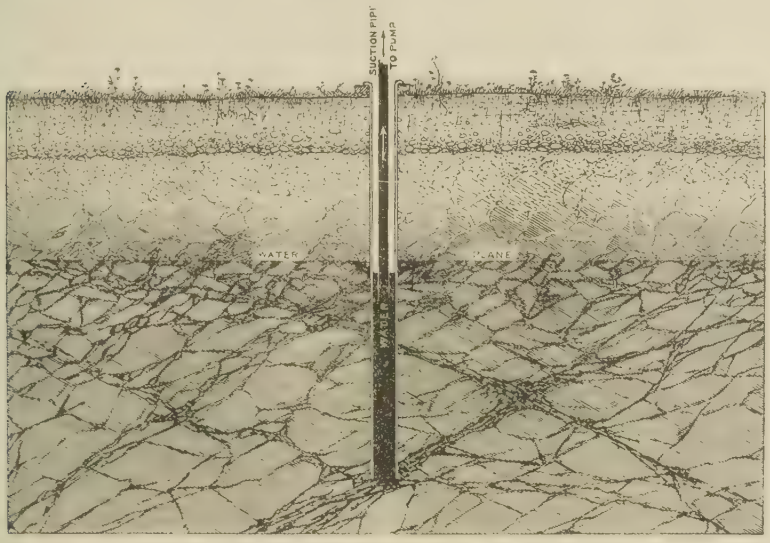


FIG. 236.—Ground water in closely fractured rock.

Water of free delivery is to be encountered in hard rock, however, in fissures as well as where artesian conditions are present, but wells thus supplied are less frequently of value where the fissures are large and encountered singly than where they are small and numerous, and in closely fractured rock the condition approximates to that in loose ground. Indeed, loose ground often grades into underlying sound rock through a disintegration zone of this sort.

That the presence of water in bed rock below loose ground is ever apparent at all, though saturation continues through all rocks to indefinite depths, is due to the fact that the many different varieties of rocks show occasional great differences as to permeability, and that occasionally also they are penetrated by fissure openings. Since among these scattered occurrences within the apparently barren zone there

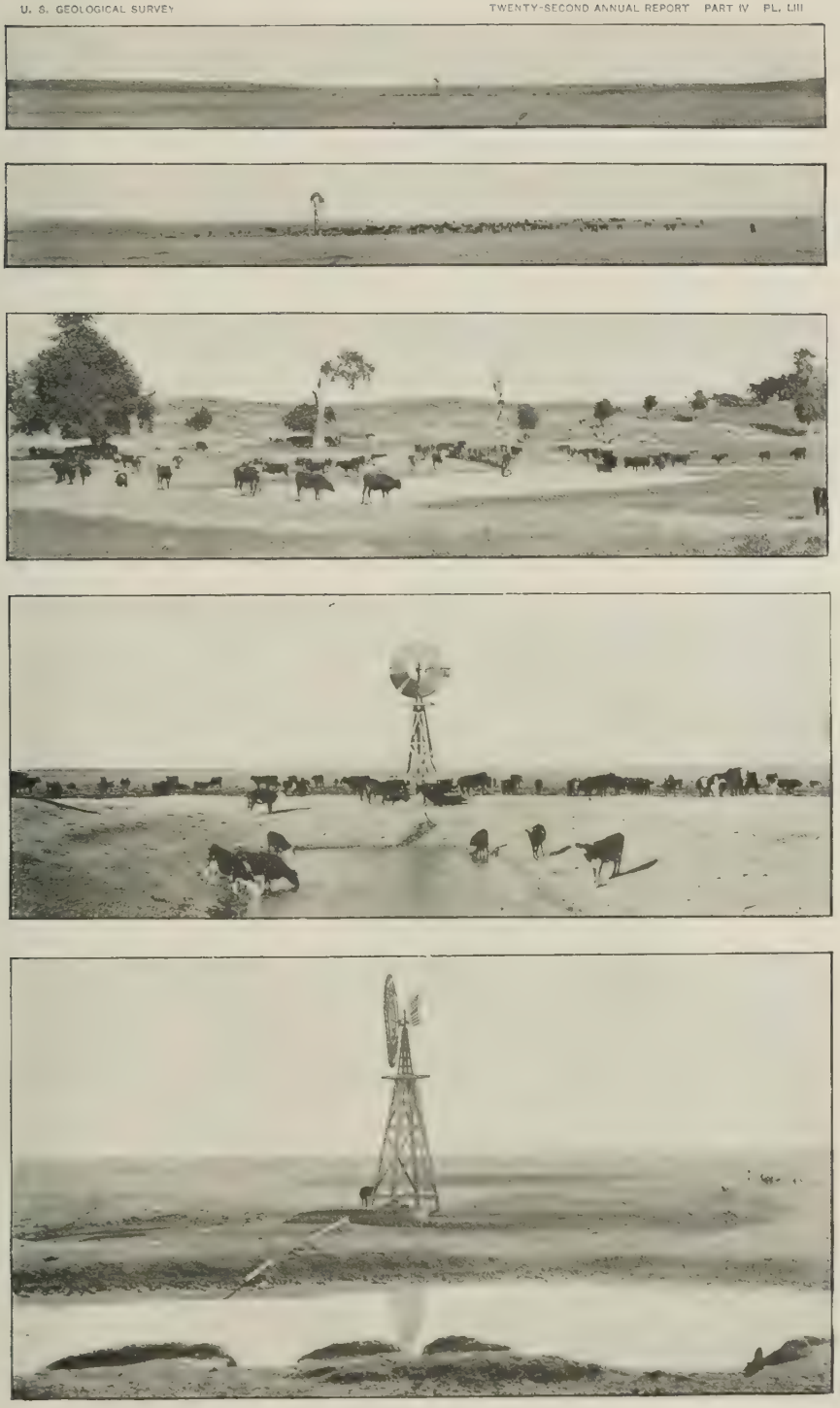
are different rates of movement, or different head pressures manifested, they are generally regarded as disconnected and independent in origin. It is not recognized that they constitute erratic drainage currents merely, along lines of relatively slight resistance, within a universally pervading water body, itself continually sinking at an exceedingly slow rate toward sea level. Hence the generally accepted term "underground waters."

In loose ground, however, the presence of water is everywhere strikingly manifest, though its volume there, per unit of ground mass, may be but little greater than in bed rock. It is obviously a continuous water body, from its definitely marked surface—the water plane—down to the bed-rock "floor." Hence, in this case, the term "ground water."

GROUND WATER IN ARID LANDS.

It is only in arid lands, as a rule, that ground water—to use the term in this restricted sense—has volume and unbroken extension sufficient to make of it an impressive phenomenon. In humid lands, coastal plains and valley bottoms excepted, it has light depth and is discontinuous, for humid lands are regions of degradation. The tendency of stream work there is to cut away and remove, not to cover. Bed rock is laid bare, except as, in its progress, the very uneven work of erosion admits, here and there, of shallow accumulations of erosion products, resulting in some depth of loose ground. Arid lands, on the other hand, are normally regions of aggradation. Their tracts of exceptional elevation aside, they are regions of universal burial. And burial, accomplished by shifting streams striving always for graded profiles, results in plains. The water plane intersects the ground surface only where the latter has marked topographic irregularity. Hence, characteristically, in arid lands, it has broad and uninterrupted extension, closely paralleling the surface. At the same time, since the loose covering upon bed rock is deep, the ground water has notable volume.

The depth from the ground surface to the water plane in these regions of light precipitation is not necessarily great. It will be slight in proportion as the gently graded surface is extensive and shows no interruption, by channeling, of its cycle of aggradation or smooth building. With indefinite extension the depth to water would be only such as would result from capillary drying. The water plane is always a mounded surface dipping toward topographic depressions which drain off. The mounding will be gentle in proportion as these depressions are far apart. Where, on a desert plain, they are widely separated, the rate of loss by lateral movement, except in limited areas of extreme dryness, will be slower than the rate of resupply from the local precipitation together with the downward-soaking contribution from the silt-burdened streams which build the plain.



DEEP-WELL STOCK-WATERING PLANTS ON UPLANDS.

WATER LEVEL BENEATH THE GREAT PLAINS.

As already noted, it is rarely the case that plain building in arid lands continues long uninterrupted either by deformation or by change of climate. The broad aggradation surface is the characteristic, if not the dominant, feature of desert topography; it is seldom, however, without record, at least faintly made, of vertical shifting of the level of equilibrium between its antagonistic aggrading and degrading forces—a record essentially of transecting valleys, commonly, however, so widened and shallow that the more conspicuous forms are the intervalley plateaus. Usually the relief is so faint that valleys and plateaus alike lie above ground-water level. In such case the water plane is not domed beneath the plateau areas, but, on the contrary, is broadly ridged beneath the valleys, since from the intermittent flow along their axes it is built up.

As noted also, the alluvial covering of the Great Plains as it existed in Tertiary time has, in the comparatively recent past, suffered a reversal of its shaping forces from construction to degradation. The vast aggraded surface has been sharply and, in the most part, deeply trenched across by the mountain streams which formerly had spread and deposited uniformly, maintaining it against the erosive tendency of its local precipitation. Suffering now, however, from local attack, unopposed, in both an arid zone bordering the mountains and a humid zone on the east, but protected over the intervening subhumid zone by a covering of sod, the original smooth surface, as we have seen, has been almost completely destroyed, except within this intervening zone of the High Plains. Within the two eroded zones, the water plane presents a surface of complex grades. Beneath the High Plains it has virtually horizontal extension for great distances. Even here, however, it does not have uninterrupted extension throughout the length of the belt; each of the several larger streams from the mountains, which have cut deep transecting valleys, have locally drained it down. Though the mountain run-off does not always reach so far as the High Plains, its valleys nevertheless have feebly perennial flow across this region, because of constant feeding from the ground water. Beneath the intervalley plateaus the water plane lies higher than the valley floors. Within comparatively narrow marginal zones, however, it dips toward them. It dips also as it approaches the limiting escarpment on the east. Except that, as a rule, there is no westward dip, the ground-water surface in each instance may be said to be faintly domed. In the case of the Staked Plains Plateau—the most extensive of these great remnantal tables, where the Pecos River turns at a right angle from the usual eastward course and follows the mountain foot in a deep valley—there is a limiting escarpment on the west also, and the water plane, completely domed, lies above running streams on every side, depleted by them rather than supplied.

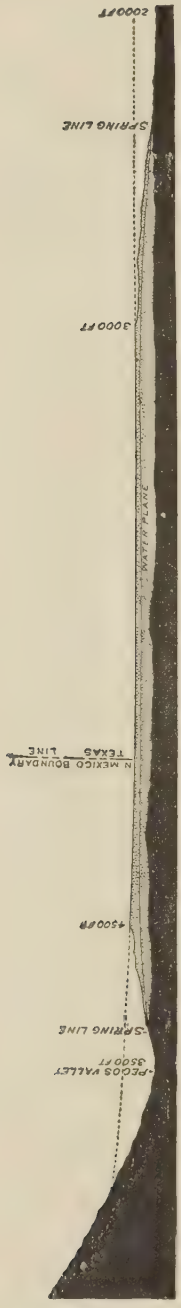


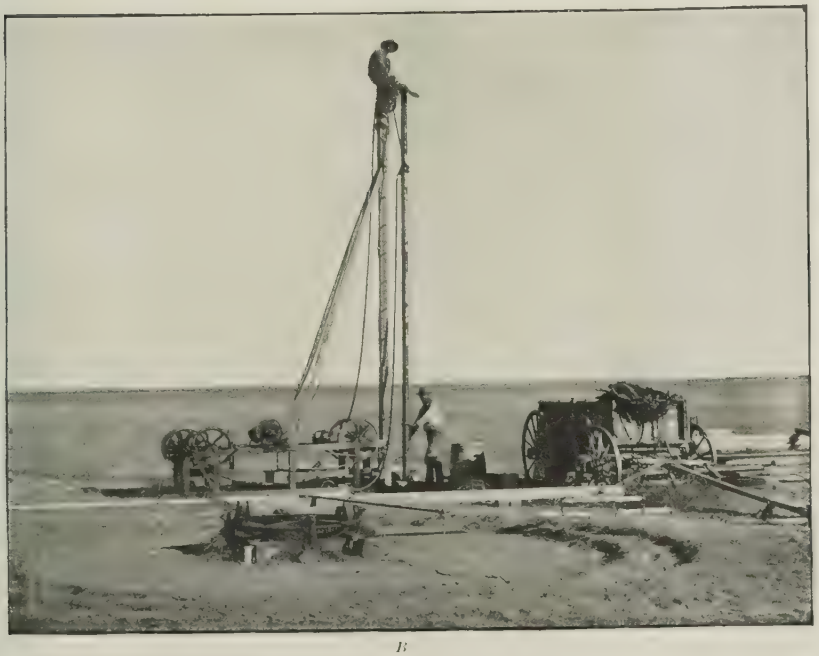
FIG. 237.—West-east section of Staked Plains plateau, showing ground-water level above that of limiting river valleys.

It is thus because the old aggradation surface is dissected and its natural ground water drawn down, and not primarily because the precipitation is light, that the water level beneath the High Plains lies comparatively deep. For these plateaus of alluvial material its depth is fixed on the one hand by that of valley dissection and on the other by the rate of supply from precipitation. If the old Tertiary plain had not suffered a downward shifting of its stream grades, the depth to water would be comparatively slight despite the semidesert precipitation.

For example, the great wash plain of the Sonora River, in northwestern Mexico, extending fan-shape for 75 miles from its canyon opening at the foot of the Sierra Madre to the Gulf of California, has a very arid climate. The river is intermittent from a point a short distance out upon the plain. Beyond this point the intervals of no flow continue through the greater part of the year. During its period of flood the stream, immediately after leaving the mountains, takes long, swinging, and subdividing courses, but probably not once in a decade does one of these reach through to the arc-form shore of the sandy waste at the gulf. Yet the whole area of perhaps 2,000 square miles, with uniform and gentle inclination seaward, is underlain by water at easy pumping depth. A well within a short distance of the coast reaches water at a depth of 8 feet—still a little above sea level and fresh. The flat expanses of the Mississippi Valley have little advantage over this desert tract as regards accessibility to water in the ground.

But in this case, unlike that of the High Plains, the surface is at grade; there are no dissecting valleys. Should uplift, however, cause the Sonora River to deeply trench the plain, the ground-water level would sink—not correspondingly, but to a considerable depth—and would acquire a stronger inclination from either side toward the river than at present it has seaward. Under this changed condition of valley dissection and drainage the desert precipitation alone, unlike that of a humid region, would not be able to hold the water level close to the ground surface. The river, then confined to a single

A.



B

DEEP-WELL MAKING ON UPLANDS

channel and sunk into the plain, would no longer add to the ground-water supply, but, on the contrary, while losing nothing except by evaporation, would be augmented from the ground water and made perennial.

In like manner it is because of the relatively deep erosion by traversing streams from the mountains, which have blocked out the subhumid belt into plateaus, that the ground-water level of the High Plains lies below economical pumping reach—that is, economical for operations, such as irrigation, calling for water in large volume. If the limit from this point of view be taken to be 15 feet, the average depth to water, even the minimum depth, is greatly in excess of it. The water plane upon the uplands is seldom to be reached within a depth of 50 feet, and upon the Staked Plains, beneath considerable areas, it may lie as deep even as 200 feet.

But while the depth through dry ground to water is considerable, it is notably less as a rule than the depth through saturated ground to bed rock. The ground water of the High Plains, therefore, has large volume, as well as unbroken and nearly level extension of its upper surface for great distances. It is in consequence an impressive phenomenon.

Its volume is less in marked degree, however, than if the climate were humid; beneath plateau areas of such dimensions its level in that event would lie close to the ground surface. By transecting valleys, relatively shallow and far apart, it would not be materially drawn down. It would be an even more impressive phenomenon than the ground water of the High Plains presents. But humid lands above base level do not afford opportunity for such broadly extended and deep accumulations of water in the ground, since they are regions of degradation, not of burial. Primarily, in fact, the phenomenal feature here is the mantle of "Tertiary gravels." Though the quantity of contained water is large absolutely, it is small in comparison with the possible content.

ORIGIN OF THE GROUND WATER OF THE HIGH PLAINS.

There is a prevalent belief that means will be devised by which, acre for acre, this great accumulation of water within the ground may be put to irrigation use upon the surface. At the same time a notion, finding expression in the generally accepted term "underflow" and involving serious error so far as contemplated results are concerned, prevails, also, to the effect that the ground water has lateral motion fairly comparable to that of surface waters—i. e., that it is continually renewed at such rate that it would be inexhaustible as a supply for irrigation.

The term "flow," used in this connection, is as inappropriate as the term "velocity" would be if applied to the motion of the hands of a

watch. That in some degree there is drainage off must be admitted, since water saturating porous material, however close textured, can not be conceived as remaining permanently at rest, with its surface at a grade. And since the sloping surface is maintained—i. e., the water plane holds virtually a stable position—there must be resupply at a rate equal to that of the loss by drainage.

The serious error here involved rests upon the assumption, which is necessitated, of a rate of resupply beyond the possibilities of even the most humid climate. Even though artesian sources be appealed to (and all rising subterranean waters are essentially artesian), ground water everywhere must be conceded to have its ultimate origin in precipitation. The water of saturation in the land masses is an outcome of the endless process by which free water, lifted from the sea and transported in the atmosphere, is showered again upon the land. The volume of water in loose ground everywhere is immeasurably greater than that of the surface run-off. The latter is virtually but the surplus over saturation. On the assumption of symmetrically domed land masses, there would be no feeding from the ground water into topographic depressions in the effort to attain uniformity of water-plane grade. There would be no spring-fed streams. In such case, run-off would be strictly a surplus; saturation would extend and be maintained close to the surface.

The volume of all the streams of a continental area is insignificant as compared with the volume of the water held in loose ground beneath. Yet the direct contribution from precipitation to streams is much larger as a rule than to the ground water. Obviously, therefore, the great volume of the latter is not to be regarded as other than the storage outcome of slow accumulation. Porous saturated ground is in effect a reservoir—filled to the brim, indeed—but receiving and discharging only a diminutive stream. Its contained water, as compared with that of streams upon the surface, is imprisoned and virtually at rest. Such movement as it has, against the enormous frictional resistance of the ground particles, either bodily or in what may be termed its currents, following gravel courses, must be very slow. The volume of the loss which the whole body of the ground water sustains annually can be no greater than that of the contribution to it annually from precipitation. And since the absorbed portion of the precipitation is such an insignificant quantity comparatively, the rate of ground-water drainage movement must be proportionately slow. This absorbed portion, under average climatic conditions, can be a matter of but a few inches. Over the Staked Plains the mean annual fall is about 15 inches. There is reason to believe that, for that area as a whole, not more than 3 or 4 inches, first and last, escapes evaporation and makes contribution to the ground water. Measured as ground water—filling the ground pores only—its depth would not exceed a foot.

A. CANADIAN RIVER IN NORMAL FLOW.

B. CANADIAN VALLEY AFTER HEAVY FLOOD.

Thus, acre for acre, to withdraw even so little as 3 or 4 inches for application in surface irrigation would leave the ground water unreplenished and result in increase of the pumping lift by a foot in a single year. Even on the assumption that lifting from the present depths would be economically practicable, the withdrawal of an amount sufficient for irrigation would rapidly result in exhaustion of the stored supply.

It might be objected that generalizations as to continental areas do not necessarily apply to limited areas, such as that of the great débris plain of the Sonora River. There the ground water, lying close to the surface, in a desert climate, obviously, in large part, is supplied from the stream to which the plain owes its origin. It is not an accumulation from local precipitation. One of the misconceptions involved in the popular notion as to the origin of the Plains ground water is that it, in like manner, comes from the mountains. But, as we have seen, the thick mass of the Tertiary gravels, though spread originally as a unit, by a parallel system of fan-building rivers, is now above grade and much eroded—with large fragmentary areas in a central zone, however, left undisturbed. Here the mountain streams, sunk in transecting valleys, no longer serve, like the Sonora River, to build the ground water to a relatively high level; on the contrary, they drain it down, even below the level at which precipitation alone would sustain it. The ground water of these fragmentary tables of the old plain has its origin in the precipitation upon their extensive surfaces alone.

There is a single local exception to this rule of stream depletion. The Arkansas Valley near Garden is shallow, though wide. The direction of slope of the ground water here is southeastward, toward the "breaks" and deeper valleys in that direction; and, for a few miles, the river, on a more nearly eastward course, runs on a level with the ground-water surface, though at an angle across its slope, so that the dip of the water plane is toward it on the north and away from it on the south. From the mountains to this point, however, the dip on each side of the valley is streamward; to the east, for a considerable distance, it is on each side away; that is, to the westward the river runs below the upland level of the ground water. The ground water there contributes to its flow. To the eastward it runs above, and is depleted in turn. In the neighborhood of Garden the river receives contribution on the one side, and on the other loses.

The Arkansas, along most of its course across the High Plains, has changed its habit, from degradation back again to building. There are topographic evidences to this effect for 50 miles eastward from Dodge. There is strong suggestion that by fan construction in the High Plains region it has lifted itself out of a former deep valley and shifted to another course, the deep valley thus abandoned being that now occupied by the feeble Cimarron. In other transecting valleys terracing

is suggestive of vertical shiftings of the level of stream equilibrium; but there is no other instance, so far as the writer is aware, of valley abandonment by this process.

Since the plateau areas north of the Staked Plains are not separated from the arid zone on the west by an escarpment facing in that direction, it necessarily follows that their ground water is to some extent replenished from both surface and underground drainage passing eastward. On the other hand, those valleys extended from that zone which, within the High Plains belt, are sunk below the level of its

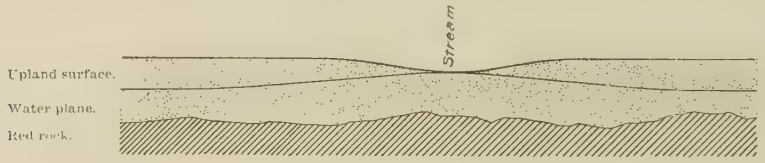


FIG. 238.—Mountain stream of perennial flow contributing to Plains ground water.

ground water, have doubtless, by their drainage effects, more than offset this small gain.

A stream from a mountainous area may have perennial extension for some distance out upon a desert, though lying above the general ground-water level there. Immediately beneath, however, the ground water will be ridged, or, in cross section, mounded, to meet it, as shown in fig. 238.

As before stated, the perennial stream normally lies below the general level of the ground water, and is persistent during intervals between storms for the reason that it then receives ground-water contribution. With many streams no exception is to be made to this

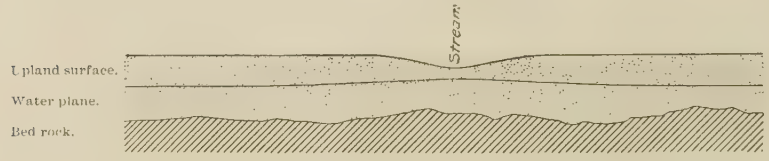


FIG. 239.—Mountain stream of intermittent flow contributing to Plains ground water.

rule; they are spring-fed throughout, without flood flow of importance. The Cimarron, in southwestern Kansas, is an illustration in point; flood flow in the upper branchings of its canyon, which has origin wholly upon the Plains in the arid zone, rarely reaches so far; and no flood flow of consequence, as we have seen, originates within the zone of the High Plains. But partial exception at least is to be made, in arid lands, of those streams which, spring-fed in relatively large headwater regions, have perennial extension into regions of ground absorption. While such streams are not thus locally perennial because of local contribution from the ground water, they neverthe-

A

B

BEAVER RIVER IN FLOOD

less invariably lie in contact with it, though above its general level, and because, locally, they build it up. Smaller mountain streams, which become intermittent tributaries to the larger before reaching the High Plains, make contribution to the ground water without lifting it into contact, though mounding it, as in fig. 239. This mound, or ridge, following the stream course, rises and subsides again after each

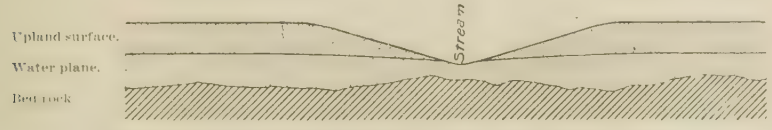


FIG. 240.—Mountain stream of perennial flow draining Plains ground water.

period of flow, and in subsiding some small increment of height is made to the general ground-water level.

But none of these valleys lying above the ground water have extension eastward so far as the High Plains. The Arkansas for a short distance near Garden, as we have seen, contributes to the ground water on the one side, but receives drainage from it on the other. There is,

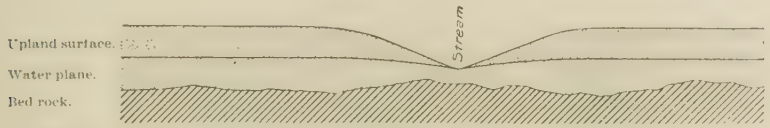


FIG. 241.—Mountain stream of intermittent flow made perennial by contribution from Plains ground water.

however, no other instance on the High Plains of a feeding supply from streams, either perennial or otherwise, which have origin in the mountains. These streams all run below the general ground-water level, drawing it down. Either they have perennial flow throughout, as in fig. 240, or, having intermittent flow originally, they become perennial by ground-water contribution, as in figs. 241 and 242. Of the latter class a special case, illustrated in fig. 324, is presented by

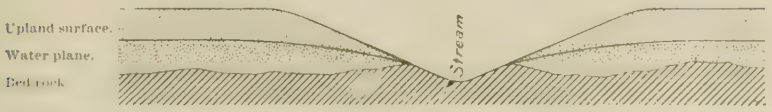


FIG. 242.—Mountain stream, either perennial or intermittent, sunk into Plains bed rock, spring-fed along base of Tertiary.

those streams (either perennial or intermittent originally, but become perennial at last by reason of ground-water feeding) which receive contribution along "spring lines," above their valley bottoms on either hand, marking the contact of the Tertiary with its bed-rock floor.

A stream like the Arkansas in the neighborhood of Garden, which goes dry only during short periods annually, will show water during these periods within a few inches beneath its sandy bed. In the hol-

lows of this bed pools may form, and these pools may, here and there, have feeble rivulet connections. They continue to hold water despite evaporation, obviously because they are continually resupplied from beneath, maintaining the water-plane level. In a mountain canyon, where the gravel bed not only is shallow but has no greater width than the stream at its flood stage, if the periods of no flow be very brief, there will be presented the same phenomenon of water just beneath the surface. It is owing to this fact that the term "underflow" has come into use. In such connection the expression is not misleading, though involving an exaggeration. On much steeper grades, and in coarse material, there is in fact down-grade movement at a measurable rate. The term at first was borrowed to apply to the water found in comparative abundance beneath the broad "sand-wash" floors of the Arkansas and the Platte during their dry periods. But wells sunk upon the gently rising valley slopes at increasing distances back from the stream, and finally upon the uplands, disclose the presence of water universally extended at apparently the same elevation as in the valleys. It was sometime later that careful leveling brought out the fact that this elevation increased, at first somewhat rapidly and then gradually, toward the plateau interiors. As wells at the outset were not tubular and deep, but of the dug variety, penetrating only 3 or 4 feet into wet ground, the term "sheet water," or "sheet flow," rather than "underflow," was first employed. The ground water was assumed to be the product of widely extended seepage from the rivers. When in the sinking of deep tubular wells in search of artesian waters it was found to continue downward, with the same freedom of yield to pumping, through a great thickness of loose material, it was assumed to have origin at points remote and indefinite. This view naturally resulted from the widely prevalent belief that the whole mass had motion at a rate comparable to that of surface waters on similar grades. Among the indications appealed to in support of it there are none which bear examination. While it is true that there is motion of the whole in some degree, it is accomplished mainly through the gravel courses, and, since the gravel courses make up but a small part of the Tertiary mass, this current motion through them must be relatively rapid. As may be experimentally shown, however, it is in fact inappreciably slow. The indications referred to consist in visible motion in dug wells during the course of excavation after the water level has been reached. In the writer's experience these are due invariably to unequal rates of response to the local head induced by pumping, where the excavation, at a single point, has cut into a bed of coarse gravel.

That the source of the ground water is the local precipitation is obviously true in the case at least of the plateau mass of the Staked Plains, where, as we have seen, the ground-water level lies high above

WILD-HAY BOTTOM IN A SPRING-STREAM VALLEY.

limiting valleys on all sides. And since the Staked Plains plateau constitutes much the largest unit among the uneroded upland areas it is reasonably clear that this must be essentially true of the whole. It is not the volume of the ground water which is the difficulty, but the assumption of an appreciable rate of motion. The volume contained within the Staked Plains table is equivalent to a depth of 25 feet of free water covering the whole. Regarded as a stream, and this idea is involved in the term "underflow," having uniformly this unusual depth, it would be 300 miles in breadth, and, assuming the barely perceptible rate of motion of a foot a minute, it would advance the average width of the Staked Plains in a year so that over 25,000 square miles a depth of 25 feet of water would be renewed annually. It is clear that the ground water is virtually imprisoned, and that upon the High Plains its mean annual depth of renewal (which gives a comparative measure of such motion as it has) is no more than a fractional part of the semidesert precipitation.

It is not to be assumed that contribution of even this small amount is made uniformly over the whole. In proportion as fine material makes up the body of any alluvial mass it will have the larger area of exposure at the surface. Concentration of standing water in the numerous basins, by diminishing evaporation, increases absorption; but the sand and gravel exposures constitute probably the principal areas of intake. These would be relatively small in their sum, especially since the old plain, abandoned by its continually resurfacing streams, has acquired, as a result of decay in place, a nearly universal "adobe" covering; but their area is increased by drifting sand, which here and there occupies considerable tracts. Perhaps one-tenth of the total surface of the High Plains is thus covered. The actual drifting—that is, the rate of travel in the direction taken by the prevailing wind—probably is very slow as compared with that in truly arid lands, for grass forms a protecting cover here also; but these tracts have the characteristic ridge-and-hollow topography, nevertheless. This open-textured character of the material (the carpet of grass of the tall varieties peculiar to sandy ground affording both shade and wind protection), together with the pitted character of its surface, must so reduce evaporation that nearly the whole, rather than only a small fractional part, of the annual fall becomes absorbed. There is hard ground beneath (the drifting sand merely rests upon the adobe surface, as deep wind work occasionally reveals), but the superficially absorbed water is held long in contact with it.

As a result of such broad areal irregularity in the depth of the annual increment to the ground water, the water plane should be irregularly, though broadly and faintly, undulated. The upland flats, so called, are not strictly level, even across the direction of their normal slope. Long lines of instrumental leveling, far exceeding the

reach of vision, often show considerable variation in elevation. This apparent warping may be in part original. Much of it, however, as we have seen, is probably due to uneven settlement. Variation in the depth to water upon the uplands, even on the assumption of a smoothly sloping water plane, is therefore to be expected, but the water plane itself, independent of the surface undulations, is out of level also. There is actual range of variation amounting sometimes to as much as 150 feet, and this at distances apart not greater than 50 miles.

Summing up, then, for the ground water, it lies much too deep to be economically available for irrigation. This fact should be obvious, in view of the experience in irrigation from wells on the low bottom-land benches of the valleys, especially the valley of the Arkansas, at Garden, in western Kansas. From such experience it has been made plain that, even upon bottom lands, it is only upon areas which are exceptionally "shallow to water" where such irrigation pays. Moreover, it has been amply and repeatedly demonstrated, by actual trial, that irrigation upon the uplands is impracticable. Though the ground water has large volume, since the depth of loose ground in which it has been accumulated is great, it has origin solely in the local precipitation of but 15 inches annually. A fraction only of the precipitation is contributed to the ground water, in replenishment of its gradual drainage losses. Only a fraction, again, of this insignificant depth of annual increment would be available for general irrigation. Thus, aside from the insuperable difficulty, from a practical point of view, presented by the high pumping lift, the annual application at the surface, acre for acre, of a foot or more of water, in irrigation, would result in lowering the level of the ground water at the rate of 3 feet or more annually, and in early exhaustion of the stored supply.

SUMMARY OF WATER RESOURCES.

The seemingly possible sources of supply for irrigation of the High Plains are three, namely, the mountain streams, artesian waters, and the ground water.

For the best economic result upon the arid plains as a whole, lands nearest the mountains should first be served. With complete storage of the surface run-off from that area in the mountains which has drainage eastward, the supply would still be insufficient to reclaim the total of fertile, tillable, and readily accessible lands lying between the mountains and the High Plains. Disregarding the claims of this intervening zone, and not taking into account the heavy loss, amounting to the larger part of the whole, which must result from such long transportation, this supply would be sufficient for only a small fraction of the High Plains themselves. The streams which extend from the mountains eastward are not large rivers; the area in

IRRIGATION IN CIMARRON VALLEY.

the mountains which they drain—their catchment area—is small, and the precipitation there is heavy only within the relatively insignificant tracts occupied by the mountain crests.

The intake areas of the possible artesian waters beneath the High Plains are merely scattered patches within the catchment areas of the mountain streams. Because grades there are steep and bed rock is but lightly covered with loose material, much the larger portion of the precipitation is contributed to run-off. Of the small portion absorbed, but a fractional part, in turn, finds its way into artesian beds. An artesian bed can not be made to yield to the full, at the surface, the comparatively feeble volume of what may be termed its stream. The possible artesian supply for the High Plains, therefore, must be inconsiderable as compared with the volume of the mountain run-off; and this run-off, it appears, even if available, would be notably insufficient.

The ground water of the central plateau masses lies much below the present economical pumping limit in irrigation. It has large volume, but it is a stored accumulation from the local precipitation, which does not exceed a mean, for the High Plains as a whole, of 15 inches annually. Its annual increment from this source, which compensates its loss by drainage seaward, thus maintaining a stable water plane, can be at best but a few inches. The draft for general irrigation would need to be at a rate considerably less than this small rate of replenishment, to avoid serious lowering of the water plane, and such a very limited supply, even if obtained at no expense for lifting, would be of no material benefit in irrigation.

Against the High Plains, then, the absolute verdict must be that they are nonirrigable. Compared with the volume of water required, the amounts available from all sources are insignificant. There are, therefore, no means by which this central upland region may have its insufficient precipitation pieced out and be reclaimed for general agriculture.

UTILIZATION OF UPLANDS.

In showing thus in detail that for reclamation of the High Plains to agriculture general irrigation would be necessary, but that this is not possible and that they are therefore to be rated as hopelessly nonagricultural, the negative side of the question of utilization has been fully developed and emphasized.

In view of the awakened interest in the arid region it is important that it should be emphasized, for the possibilities of irrigation are not unlimited. The arid West can not thus be reclaimed entire. Even in the humid East a relatively small area only is agricultural. Though the whole is sufficiently watered, the cultivable area is limited by what is tillable, and in a region of degradation the tillable area necessarily

is small. Similarly, in an arid region, though tillable lands there make up a large part of the whole, the cultivable area is limited, in this case by the water supply. It is the theory of irrigation reclamation in an arid country that the relatively slight precipitation over the whole, so far as possible, is concentrated, in the necessary abundance, upon a fractional part. It follows that large areas well adapted to agriculture except for the lack of water must inevitably be excluded. To this class belong the High Plains.

But it does not follow that such lands may not profitably be turned to other use. In large part they support a growth of grass highly nutritious. They may therefore be utilized for the growing of stock, but to somewhat limited extent only. The natural grass crop, as a rule, is scanty, or grows in separated tufts, and value for grazing rapidly diminishes as scantiness of growth and the area required to be covered by the feeding animal increases. Furthermore, watering places are too far apart for utilization of the whole or even a considerable part; zones near to water are overfed, and stock become lean, though the interior areas remain untouched.

STOCK FARMING.

While nonirrigable, and therefore nonagricultural, the subhumid High Plains may yet be reclaimed for pastoral uses. Though their grass covering is everywhere abundant and of excellent quality, they meet the requirements of an ideal pastoral region only in part, so that an artificial process of reclamation in some measure will be necessary.

The broad intervalley plateaus are practically waterless. Their numerous faint depressions sometimes becomes lightly ponded, and continue so for brief periods. Ponding is the only natural reliance for upland watering, but it is at best an uncertain one Ordinarily, these grassy plains may safely be grazed only in narrow zones following their borders, from natural stock-watering points in the valleys and along the foot of the eastward-facing "breaks." In consequence, while the marginal belts as a rule are overgrazed, the interior areas remain virtually untouched. Reclamation will be by means of wells. Full utilization as pastoral lands, and uniform grazing, are to be secured only through the artificial creation of stock-watering points, in comparatively close and even distribution over the interior areas. A supply ample for such very limited use may everywhere be had by windmill pumping from the ground water.

Experiment with windmill watering, especially on the part of the large cattle companies of the Staked Plains, has not only demonstrated the feasibility of such a scheme, but points unmistakably to the disappearance eventually of these occasional large holdings, and to the establishment of a checkerboard subdivision of the whole into unit areas of about 2½ miles on a side, each with a deep well and pumping

A. HEADQUARTERS CATTLE RANCH ON A SPRING CREEK.

B. A "WATER HOLE."

plant centrally located, fenced, and in individual resident ownership. Pioneers in this work of transformation, known as "stock farmers," are already being recruited from the scattered representatives of the considerable population of a decade and a half ago, which for several years was engaged in an elaborate but disastrous experiment in general agriculture. The windmill has made the "dry claim" tenantable. The turning wheel upon the horizon is always the first evidence and the sure sign of habitation.

These individual owners are able to grow only fodder cane of the drought-resisting varieties, such as Kaffir corn, for emergency use in winter. Of more succulent feed for young or especially valuable high-bred stock, and of vegetables and fruit for his own use, the stock farmer can produce nothing. The occasional small irrigable areas within the valleys, because close at hand, will best be able to supply his needs in these respects. Little explored now, since surrounding tracts are virtually uninhabited, as is conspicuously the case in the regions traversed by the Cimarron and the Beaver, they will ultimately come to have high value.

ARTIFICIAL PROVISION NECESSARY FOR STOCK-WATERING.

The subhumid High Plains, though they must be rated by the agriculturist as within the arid region, present a marked contrast to it by reason of the thick-set character of their grass covering. On the other hand, they share with it the disadvantage of a lack of water. In fact, the wholly waterless areas of the High Plains are of considerable extent.

Previous to the agricultural invasion the High Plains, to about the same extent as the arid region generally, were made use of as a public range for cattle. Lying far removed from mountains, their broad surfaces everywhere above water sources—above springs and streams, the ground water, and the maximum rise of all artesian waters—they could safely be grazed only within narrow marginal zones. Despite their superior carpeting of grass, therefore, they are only in small part a pastoral country. In a measure, a process of artificial conversion will be necessary. Even to the stockman, these extensive interior areas of grass land are in effect desert. Artificial watering, providing a drinking supply for stock at points in systematic and close distribution will reclaim them entire. The ground water, by means of wells and windmills, will be the source of supply. Because of the higher value of the smaller quantity required to this end, it will be easily within economical pumping reach. And the supply, even regarded as no more than the inch or so of annual increment to the ground water from local precipitation, will be safely in excess of requirements.

Formerly, under most favorable conditions, only valleys of tran-

secting mountain streams and the zone of springs at the foot of the eastward-facing escarpment could be utilized as breeding grounds; the upland flats were feeding grounds merely. As the difficulty with the High Plains generally is simply their lack of stock-watering places, to provide these in great number, evenly distributed at the necessary short distances apart, will result in transformation of the whole into breeding grounds; in fenced subdivision into private holdings—at first, as a rule, of great size and multiple ownership, but eventually and inevitably of individual ownership and comparatively small size; and in a light resident population correspondingly distributed. The number of cattle which may be grazed to the best advantage (sheep being debarred apparently by the extent to which conditions favor drifting snow in winter) will be very greatly increased. The necessity for long-distance driving and rough usage in general will be almost wholly done away with. The hard-riding cowboy of the earlier period will disappear with the development of the inclosed rectangular "pasture." The amount of "handling" of stock required, and therefore the number of men and horses necessary for that purpose, will be largely reduced. In other words, artificial watering will not only greatly expand the area especially adapted to stock-raising, and to nothing else, it will occasion a radical change and make possible a notable improvement in the methods of stock-raising generally. Accomplishing a large reclamation at small cost, it will eventually result, through elimination of the range feature, in greater economy of production and increased value of the product. Opportunity will be afforded also, through fenced subdivision into pastures, for maintaining a higher standard of quality.

Such opportunity the common or public range can not afford. The beginnings of a change in this direction already are noticeable. Except in northwestern Texas, however, it has hardly as yet been deliberately made. With the few who remain of the great body of settlers of some years ago stock raising is regarded as a makeshift. The lingering "farmer," in deluded waiting still for a radical change of climate, is pasturing a few cattle outside his plowed fields, growing annually a small crop of cane "fodder," of drought-resisting varieties, for tiding the young and the weak of his herd over the more severe periods of the winter season; but chiefly his efforts are devoted each year to continued experiment in wheat raising. As we have seen, he has found the deep well and the windmill necessary to his survival.[a] He does not recognize that it might be made the means as well of his comfortable support.

[a] The majority were deterred from experiments in this direction by the great depth to water. On that account a few among those who were located near the plateau margins even resorted to the laborious alternative of hauling at short intervals from the valleys and storing in cisterns. Near the abandoned town of Springfield, southwestern Kansas, the writer, in 1897, chanced upon one of these isolated claim holders, who for eight years had persisted in hauling his water by hand from the Cimarron River, 5 miles away, and who, in reply to a suggestion that water might readily be had by boring, objected that it was "about as far down as it was across."

FORMER IRRIGATION FROM ARKANSAS RIVER AT GARDEN, KANS.

These would-be agriculturists, out of place in a grazing country, are nevertheless, though unwittingly, putting it to its only profitable use. They are becoming "stock farmers."

Neither shade nor fruit trees, nor kitchen-garden produce, except in small quantities as laboriously secured luxuries, can be grown by irrigation at the average high lift; but by multiplication of well and windmill plants over the immense waterless areas in even distribution stock may be supplied with the small quantity of water they need, in numbers limited only by the feed supply, and at relatively small cost. The natural feed supply needs to be supplemented by a small emergency crop of cane fodder, for which irrigation is not necessary. In many cases the annual experiment with wheat has been abandoned for the necessary cultivation of this fodder crop. It is the occasional remaining farmer immigrant of some years ago, with his deep well and windmill, his small but growing herd, and his field of sorghum or of kaffir corn, who is known as the stock farmer, and who in fact has unconsciously worked out, or at least is indicating the solution of, the problem of the most profitable and fullest possible utilization of the High Plains.

THE NATURAL UNIT OF LAND SUBDIVISION.

The area of grass land required for the support of a single head of stock is reduced to the minimum when evenness of feeding is secured. And evenness of feeding is to be secured not alone by providing watering places in proper number, properly spaced apart, for cattle will not distribute themselves in equally divided bunches among the watering places. They quickly develop preferences, which chance seems to determine, but which are difficult to break up; and this leads to very unequal grouping, to overgrazing, and to an underfed condition of the greater number. The remedy is to be sought, after the proper spacing of watering places has been secured, in subdivision on the checkerboard plan, leaving each well at the center of a rectangular fenced inclosure.

In the arid region generally the area of grazing land required for the support of cattle, per head, under the public range method of feeding, is estimated at from 15 to 20 acres. Upon the High Plains, with their thicker carpeting of grass, and under methods of partitioning insuring even feeding, the best experience indicates that it will not exceed 10 acres. Furthermore, a considerable body of experience here also, especially upon the Staked Plains within recent years, goes to show that cattle can not be maintained in the best condition if compelled to range, in their feeding, to distances from water greater than a mile or a mile and a half. In other words, the number of cattle watering at a single well should not be so great that, allowing 10 acres to a head, the outer limits of their feeding ground will be more than

a mile and a half distant from water; and overstocking is to be avoided only by spacing wells at something less than twice that distance apart.[a] We have here, then, for the unit area, or fenced rectangular pasture of a size determined by natural conditions as economically the best, dimensions of about 2½ miles on a side. Thus this unit area would include 6¼ sections of the land survey subdivision system, or 4,000 acres. With water to be had at a central point, approximately, it would afford pasturage for 400 head of cattle.

Increase in the number of wells, unless accompanied by corresponding further subdivision, would merely lead again to uneven feeding. Any such elaborate parceling out of the public domain implies its transfer to private owership. Hence, for the individual owner, as a rule, the unite area at the outset would need be smaller. It will appear upon consideration, however, that the minimum size of his holding could hardly be less than 1,000 acres—considerably more than a square mile or full section. A square mile, on the assumption of 10 acres to a head, will afford sustenance for but 64 head, and it is generally accepted in the Plains region that whenever reliance must be had solely upon stock farming, in which cattle are the only salable product, 100 head is the least number from which the individual farmer and his family can secure profit sufficient for more than their bare support. This is assuming uniformly favorable conditions. One hundred head will be much too small a number for reasonable security against the accidents of the seasons. Thus, the individual stock farmer, in order to be fairly prosperous, will require an area of pasture land at least equal to that which the great corporation finds to be the economic minimum of its necessary checkerboard subdivision into single-well squares. The important fact should here be recognized that the unit area of 4,000 acres, in a region reclaimable by means of drinking wells to pastoral uses only, is fairly comparable in value to no more than the "homestead" unit of 160 acres in an irrigable region reclaimable to general agriculture. The index of the value of this large area is the 400 head of cattle which it will continuously support. The relative value per acre—stating the case liberally, probably—is the ratio of the annual profit from these 400 cattle, upon 6¼ sections, to that from the agricultural yield of a single quarter section; and the stock farming population will be in the same ratio.

But the High Plains will have been reclaimed and utilized. At present, except so far as stock farming in a very small way has made a beginning, they are without value; and their scientific conversion into pasture lands, aside from quieting a vexing problem which periodically has caused fruitless and demoralizing movements of population, and heavy loss financially, will add materially to the wealth of the several States of which they constitute large unoccupied portions.

[a] The writer was informed by the general manager of the largest cattle company operating on the Staked Plains that it was his intention in the future to space his wells 2¼ to 3 miles apart.

A CONFUSED MINGLING OF GROUND MATERIAL IN DUG-WELL MAKING.

B. SAMPLES OF THE SECTION IN TUBULAR-WELL MAKING.

Title to these lands, especially in western Kansas, though transferred from Federal ownership[a] almost entire, has in large part either fallen into the hands of loan companies or passed to county ownership through inability of individual claim holders even to pay county taxes. In large part, also, it is burdened with county bonded indebtedness for public improvements, dating from the boom period, and now either in ruins or otherwise valueless. In some cases the counties themselves are virtually nonexistent, so far as population and resident control are concerned. Here the stock farmer is becoming evolved from the homesteader, with his bunch of cattle, his well and windmill, and his patch of fodder cane.

The homesteader dispossessed the early cattleman of a field into which it had been the practice of the latter merely to make wandering incursions; and the few of these newcomers who have retained a hold upon their "dry claims" have been able to do so by becoming stock growers themselves. Eventually, as resident stock growers, they will cover the field; for, through the agency of windmills, pumping almost continuously from the deep-lying ground water, and requiring but little supervision, they have the marked advantage over early practice of being able both to breed and rear their stock, until ready for market, upon compact areas of excellent pasture, fenced and in individual ownership, where formerly stock could not have existed at all. The size of the individual holding, however, will need to be greatly expanded and land values correspondingly readjusted.

Upon the Staked Plains of Texas the early cattlemen have not been completely dispossessed. Not all of that great plateau was public range, and the agricultural invasion did not extend, as in western Kansas, to virtually the whole. Here, from the first, immense tracts—in one case nearly 5,000 square miles—have been held in private ownership, either individual or corporate; and it is in this region, adopting, or adapting, to his needs the results of expensive experimental efforts toward full utilization of their grazing lands by large owners, that the homesteader has become a stock farmer.

The first large holdings on the Staked Plains bordered along the Canadian Valley. The upland was used as "range," to the small extent practicable. The light incision of storm-water drainage, beginning some distance back from its margin, afforded opportunity for storage in small reservoirs or "tanks" (Pl. LII, *B*), and the marginal feeding ground by this means was in time appreciably extended; but there was no permanent occupation until resort to the deep well and the windmill began to render it possible. Private holdings upon the uplands in large blocks were then at once greatly increased.

So far subdivision of these large holdings into "pastures" has not been brought down to rectangles smaller than 8 or 10 miles on a side;

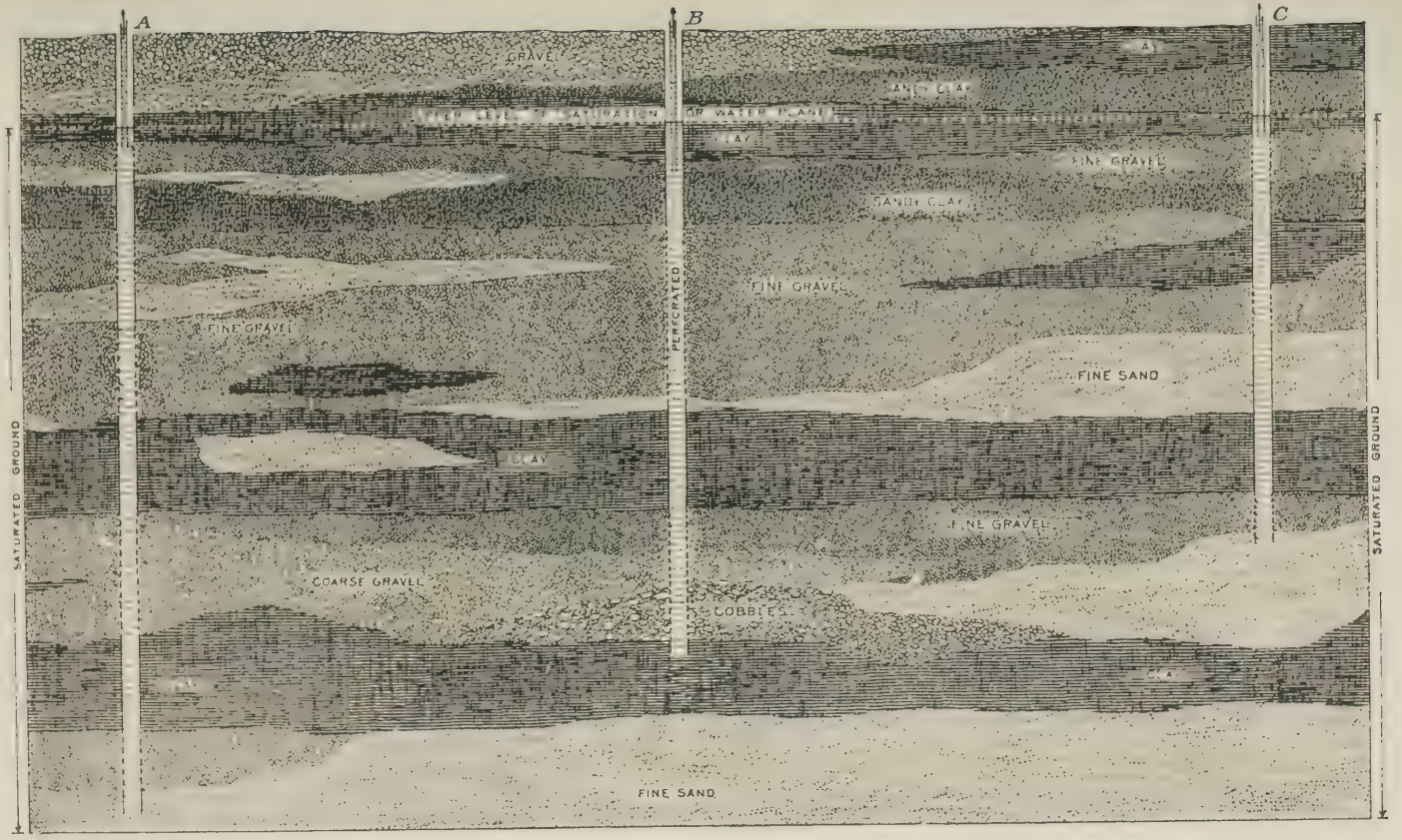
[a] In Texas public lands are the property of the State.

nor is there anywhere the systematic and close spacing of wells which experience indicates would be the most advantageous; nevertheless, the practice of artificial watering and subdivision has brought about the permanent occupation in some measure of the whole interior area.

The large owner has worked out the local problems of deep-well making. About these there was nothing essentially new, but it needed the successive trial of methods well known elsewhere in order to determine what would best meet local requirements. For there are considerable areas beneath which the depth to water exceeds even 150 feet, though the mean depth is much less. To the eye the upland surface as a rule does not sensibly depart from the horizontal; yet its extent is so great that imperceptible differences of grade, either original or occasioned by broad differential settlement, give to it undulations across the direction of general slope amounting to 100 or 200 feet at points wide apart. Furthermore, the numerous clay sheets are sometimes thick, as well as broadly extended, and have only thin beds of sand, without coarse gravel, intervening, so that it is frequently necessary, after penetrating deeply through dry ground, to go deeply into wet ground also; and the penetration of wet clay for considerable distances calls for special methods and devices. It has been only after much costly experimentation that right methods, reasonably inexpensive, have come to be adopted.

Mistakes, which experience only has corrected, have been made also as to the types of windmills employed. That which is best adapted to low lifts, for irrigation, where a large volume of water is the prime requisite, and to which can be given close and constant inspection because the area which it serves is several acres only, is not necessarily the best for stock-watering purposes. In such use the wheel must largely be left to itself; the unit area which it serves is measured in square miles, not acres; and it will best answer its purpose if, in uncommon degree, it is self-regulating and strong, requiring little inspection, since it is not a large supply that is needed but a sure one. Again, the best form of storage has been a matter of development. The dug reservoir alone falls short of requirements, though at first this fact was not sufficiently recognized. In summer cattle stand in the water after drinking from it, and keep it thick with stirred-up mud; in winter it freezes over. Pure water is needed; and for the best results it should be cool in summer and in winter not too cold. The ground water as it issues from the pump perfectly meets these requirements. It is essentially spring water, and it has a temperature, winter and summer, of 59° or 60°. A drinking tub, not too large, is provided to first receive it. The reservoir then serves a useful supplementary purpose.

The individual owner of small means has benefited by this experimental work and experience of the cattle companies. At the same



IDEAL SECTION OF BEDDING IN FREE-DELIVERY GROUND.

time, with more unerring instinct for the essential, he has gone a step further on his own account, in adding the feature of supplementary feed provision for the young and weak of his herd during the severe periods of winter. To some extent he has gone further also in providing shelter against the more severe storms in winter and the midday heat in summer. Making his beginning with several head only, to which, therefore, he had been able to give individual care, he has had more forcibly impressed upon him than the large owner the advantage, at critical times, of such additional feed supply and protection. The pioneer farmer, unsuccessful as a wheat grower, was more successful in raising drought-resisting crops for feed for cattle, and took more naturally to the idea, carrying it further than did the cattle company, operating through many employees. He will continue to be more successful in all the details of this transformed industry, because of his more direct personal interest. Upon the Staked Plains it is the prevailing impression, and it is the opinion also of the writer, that the "stock farmer," with his one-well rectangle of a half-dozen square miles, will come eventually to possess the field. He will do so because there will here be little or nothing of that advantage from large operations resulting from concentrated effort, which in manufacturing, for example, is so marked, and he will possess a field which heretofore has been, virtually, and in large part still is, a solitude—a desert of waving grass—visited by cattle at all only in brief seasons of basin ponding, as previously it had been by buffalo. The solitude will not be greatly enlivened by a population of one family to a square mile but it will be a resident population, producing abundantly for export a staple product. Upon the Staked Plains, at least, the stock farmer has already given material evidence of success.

UTILIZATION OF VALLEYS.

The valleys, though wide apart and relatively small as to their total area, will yet, by reason of their possibilities for irrigation, contribute in important degree to the full development of this pastoral region. Fodder cane will be the only farm crop which the stock farmer can produce. He will be able to supply himself with meat, and with butter and eggs; the immediate surroundings of his well, shutting out the desert, will present much of the traditional barnyard aspect; but he must supply himself with garden produce by purchase. The irrigable valley areas, because of their comparative nearness, will meet such requirements at a not excessive cost.

But the fullest possible irrigation development will be necessary. The greater portions of the wide valley slopes are merely stock range also. The areas available for irrigation on a scale larger than required for headquarter ranches located there as well, are not numerous. Only bottom lands, level and "shallow to water," will be thus avail-

able; and, in arid lands the "flood plain" of a stream is submerged and modified much more frequently and seriously than in humid lands. The illustrations of Pl. LV show the Canadian River in normal flow; the lower one, however, in the complete removal of several sections of an iron bridge, and in valley widening, which it displays, calls attention also to the overwhelming effects of bottom-land flooding.

There are exceptions, however, where, from special causes, the bottom lands are terraced, presenting two or more levels. Such a condition prevails at Garden, on the Arkansas. Again, the flooding is less serious in those valleys which head, not in the mountains, but in the western arid belt of the Plains. Such a valley is that of the Beaver, shown in Pl. LVI. It is only the tail of a flood which reaches to that section of its length where it trenches the High Plains. Here, and during most of the year, the Beaver is spring-fed. To a larger extent

FIG. 243.—Map of valley floor subject to floods, showing sand-wash belt and subdividing stream.

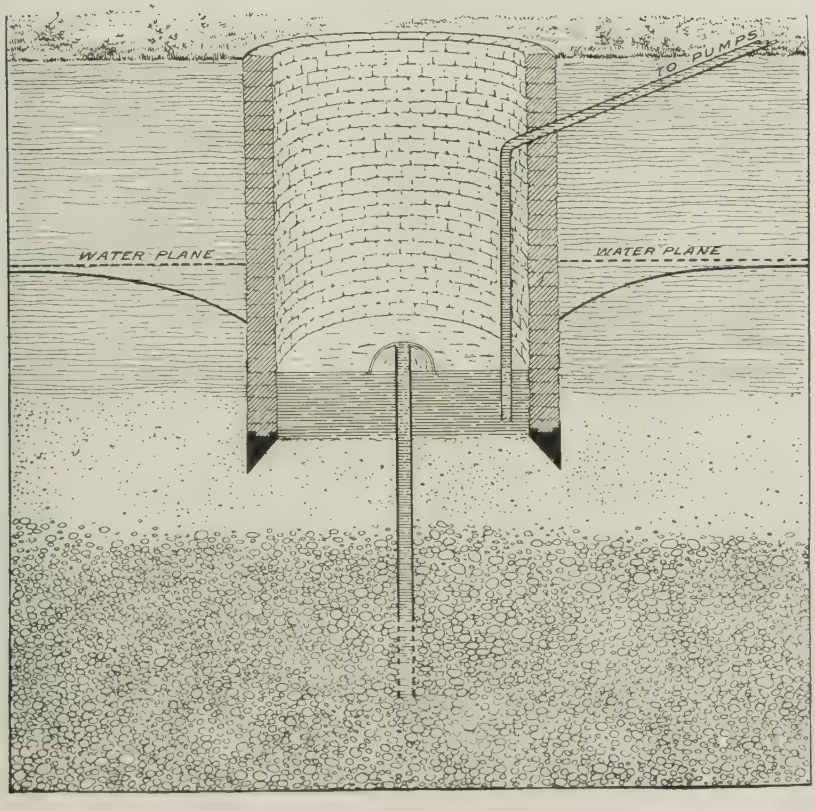
than upon the Canadian, therefore, it has bottom lands available for irrigation.

There is marked difference in the character of the bottom-land belts of these two types of valley. The desert stream of constant flow, widely variable in volume and always heavily loaded, not only overruns in some degree and sensibly modifies its flood plain at more frequent intervals than the stream of humid lands, but it subtracts from the arable area of the flood plain at low stages by maintaining a sand-wash belt within it, marking the width of its lateral shiftings.

Of this type are the valleys of the Canadian, the Arkansas, and the Platte. Their shaping streams do not meander in loops, leaving cut-off ox-bows. They dodge or subdivide upon the obstructions created by their temporary deposits, shifting laterally in considerable sections.

The High Plains, as we have seen, do not give origin to such streams, characterized on the one hand by annually recurrent flood-flow and on the other by a heavy burden at all times of erosion products. They do not feed their drainage channels by surface run-off, but from the

A. CITY WELL AT GARDEN, KANS.



B. SECTION OF CITY WELL AT GARDEN, KANS.

ground water. Those valleys which head within the arid belt, carrying merely the desert-plain run-off and receiving nothing from the mountains, send tail-floods into and across the High Plains belt only at long intervals. The valleys themselves are the work of these floods of exceptional extension; but, sunk thus below the ground-water level, their normal flow is spring-fed locally, and without the heavy load which leads to spreading by subdivision. It follows single channels. There is no appreciable subtraction from the bottom-land width, since the spring stream is without the sand-wash belt, which is virtually the bed of the silt-burdened stream—diminutive, but of multiple shifting channels. Upon a flat floor of gentle grade the spring-stream intricately meanders. The floor is thus inconveniently cut up; but it is almost entirely arable land and rarely suffers damage by flood.

In striking illustration of these radical differences of stream behavior, under the conditions of full load and relatively light load, respectively,

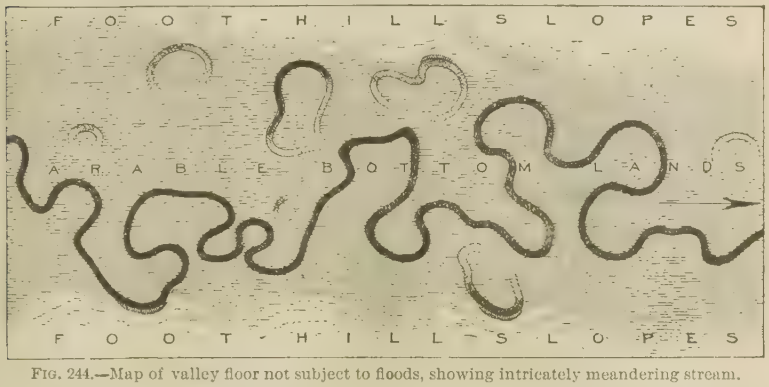


FIG. 244.—Map of valley floor not subject to floods, showing intricately meandering stream.

are the Platte and the Missouri, in the region of their junction, excepting a canyoned length of the former just previous to junction. The Platte subdivides and reunites in many shifting currents. In its upper course the Missouri has this habit also, but here it normally follows a single looping channel. During its frequent periods of flood and of broad submergence it is notably a fully loaded stream, not moving all of its load in suspension, but dragging a portion in shifting deposits. As a rule, however, it has essentially the character of the desert spring creek upon the floor of a long-interval intermittent stream, holding a sinuous course of uniform width, adding to one side what it cuts away from the other.

A notable example of such a valley floor, almost unvisited by run-off floods, yet with a perennial stream of constant volume looping intricately upon it, is that of the Cimarron along much of its course across the High Plains. The spring stream here merely occupies the valley; it has no part itself in valley making. It does not run full length.

Though in some of its live sections it is a strong stream, unvarying in volume, there are other sections in which the bed is permanently dry to depths of 20 or 30 feet. Pl. LVII presents a scene in such a dry section, where, however, the ground water lies at a very light depth. As elsewhere, under like circumstances, wild hay is cut here for winter feed. It happens that the Cimarron Valley floor lies approximately at the ground-water level, though not precisely. At one point it may be a little above, at another a little below.

A few miles above Arkalon, in southwestern Kansas, there is a feeble "reappearance," as it may be termed, of the Cimarron, following a long dry section. A few miles below Arkalon the flow is 82 second-feet. At the point of beginning the general water-plane level beneath the uplands on either side is but slightly above the stream; here it is 35 feet above. Downstream the volume of flow again dwindles, the depth below the water plane diminishing also, until within a few miles again flow ceases entirely. Here, as well measurements in upland wells indicate, the relative water-plane position is reversed. It lies slightly below the stream end, which, showing no lessening in the velocity of flow, nevertheless maintains very nearly a fixed position. The spring stream, passing fan form into the dry ground, builds upon the water plane, as above it had created locally a depression. Just beyond the Kansas border, southeastward, there is reappearance from the dry stream bed again in even greater volume. This alternation of wet and dry lengths is repeated upstream also from Arkalon.

Wherever within the High Plains belt the Cimarron Valley shows a living stream it is always a meandering, looping stream of uniform width, narrow, clear, and deep, in ground plan having the general character represented in fig. 244. The bottom land upon which it wanders supports a coarser and longer-stemmed grass than the uplands, the grass roots reaching to the ground water, which lies at a depth here, as a rule, of only 2 or 3 feet, grading gently inward to the stream level. The whole area is easily irrigable.

From the first, so far as practicable, these spring-stream bottoms have been utilized for stock-ranch headquarters. They have not been utilized to the full, since such ranches can not, in the nature of the case, be located close together. And as irrigation commonly has been practiced merely to supply garden products for individual ranch needs, they have been irrigated only in small part. But eventually they will receive the highest possible irrigation development. They will then contribute largely to the success of upland stock farming.

At a point on the Cimarron where its valley bottom is abnormally broad—the Englewood Basin—a beginning in irrigation has been made which, in a striking manner, illustrates the possibilities (Pl. LVIII). Here, by ditch diversion, 1,200 acres are watered, and yet about a third only of the perennial run of the stream is utilized.

DISCHARGE OF FEEDER IN CITY WELL AT GARDEN, KANS., DURING HEAVY PUMPING.

These spring-stream valleys are especially a field also for irrigation by windmill pumping from the ground water. The phenomenon of interrupted flow—i. e., of disappearing and reappearing streams, so called—is common. That is, erosion, by floods having origin in the arid belt at intervals of groups of years, readily cuts valleys to the ground-water level; it does not so readily, however, cut below that level. It is only the larger mountain streams, of nearly continuous flow and heavier floods, which show high-level spring lines, indicating deep cutting below the water plane. As soon as saturated ground is reached, its inward creep tends to refill the excavation, during the long interval between flood runs. The valley is thus built up to a flat bottom having the meadow aspect. It is because of this tendency of ground water to hold the floor of a valley of such little-used type close to its own level, and because in the nature of the case it can not do so perfectly, that in this region perennial streams of interrupted flow—in alternate dry and wet sections—are of frequent occurrence. The water plane is never either high above or deep below the valley bottom. Hence, along the dry sections it is commonly within easy pumping reach. But more commonly it lies just below, since refilling by creep, on gentle slopes so close to saturated ground, is readily accomplished. Thus it is principally these sections, having the general aspect presented in Pl. LVII, and often supporting a growth of tall-stemmed "wild hay," the roots of which, unlike the grass of the uplands, are able to reach water, which are destined, as oasis strips, to supply garden produce to the High Plains.

Many self-supporting ranches will be located upon the long slopes of the larger valleys, several of which, like the Canadian, are sunk not only below the general ground-water level, but deep into the relatively impervious rocks underlying the Tertiary. These ranches will have position at points of exposure of gravel beds along the characteristic "spring-line" at the base of the Tertiary, also occasionally along higher spring-lines, of less positive definition, marking the outcrop levels of widely extended mortar beds.

Midway of the north slope of the Canadian Valley, marking the contact of Tertiary and Red Beds here, is a cattle ranch (that of the Reynolds Land and Cattle Company, on Romero Creek) making excellent use of a spring discharging nearly 2 second-feet. This spring has extension as a stream, for about 2 miles, onto a broad terrace flat. Here the ranch is situated. The full available supply from the stream is not utilized, since the out-of-season flow is not stored; but during the growing season the whole stream is applied in irrigation to the best advantage. This point is the center of control for an area grazing 9,000 head of cattle. It is also the distributing point for supplies to a number of minor outlying headquarters. The ranch buildings are heavily shadowed beneath many shade trees—cotton-

wood, locust, willow, ash, and osage orange; an orchard of several acres furnishes a superabundance of apples, peaches, apricots, pears, nectarines, plums, and cherries; there are arbors of grapes of several varieties, and a garden supplies a surprising assortment of vegetables. An artificial pond produces carp and sunfish; it also yields ice in winter[a] for the preservation of meat and dairy products through the very hot summers—an important innovation in stock-ranch life. In addition, 30 acres are grown to alfalfa, for winter feed for cattle. Storage is in contemplation for increase of this feed crop. By devoting the entire annual flow of the stream to stock feed, supplying orchard and garden from windmills, it is estimated that 1,000 acres may be reclaimed for alfalfa.

Few springs afford so large a flow as 2 second-feet and at the same time occur within reach of irrigable lands. But this ranch (Pl. LIX, A), like many others, is the headquarters for an area which, it would seem, must eventually come into the hands of many individual owners, the majority of them upon dry claims. It will in that event find a ready and profitable market for its present oversupply of fruit and vegetables.

Less important, though more numerous, than the springs and perennial streams, are the "water holes" (Pl. LIX, B). These occur where the stream bed lies so close to the water plane that scour troughs, exposing it, are created by occasional run-off floods. They differ from the spring streams in that they have such short length that motion is not perceptible. Arroyo beds which lie above the water plane exhibit pools of standing water in their hollows after flood runs, but only for a short time. Ground absorption and evaporation soon cause them to disappear. The pools of the characteristic water holes, however, are perennial, or if shallow they may for a time fail, through a few inches of lowering of the water plane during exceptionally dry periods.

They afford natural watering places for stock. But what is much more important, they occur in areas shallow to water—windmill areas. Furthermore, by a little simple engineering they are usually convertible into light-flowing spring streams. Water holes as a rule occur in chains, either of disconnected links or of links feebly connected in groups of two or three. They indicate a limit to valley deepening, which the ground-water level has fixed—a limit easily reached, but to be passed only by streams of frequent flood flow. Valleys that are subject to heavy floods only at long intervals commonly exhibit this almost precise agreement in position of the valley floor with the ground-water level. A ditch in dry ground may usually be dug narrow and with upright sides; but after wet ground has been reached, either the width must be increased or excavation must proceed more rapidly and repeated thereafter at short intervals. The tendency is for creep from either side to cause the banks to recede and the ditch to refill to the water level, creating a wide floor. Broad, waterless valleys, with

[a] The elevation above sea here is nearly 5,000 feet.

MAP SHOWING DISTRIBUTION OF WINDMILL PUMPING WELLS ABOUT GARDEN CITY, KANS.

water just below ground, however, or actually appearing in exceptional hollows, are therefore of not unusual occurrence in the subhumid belt where flood runs come from a distance.

The springs and spring streams have all been occupied as ranch locations from the early years of the stock industry. At few of these ranches, however, has more than a beginning as yet been made toward development of the local possibilities for irrigation.

Such full development of the minor valley patches must await the partitioning and settlement of the upland stretches, creating a market for garden produce. Possession of these favored localities, which will acquire relatively high value, will then pass naturally from the stock-farmers, to whom they will not be vitally necessary, into the hands of agriculturists proper. They will be utilized as truck farms, exhibiting, of necessity, the application of water in garden irrigation by methods the most economical and scientific.

In like manner, in the larger valleys, terrace levels of their floors, exempt from damage by the annual floods, will be utilized to the full. The Canadian and the Smoky Hill, cut relatively deep, have only occasional and small areas of this character, though such as they do afford will acquire high value. There is here a deficiency of irrigable lands. Stream flow is in excess of these small needs. The Beaver and the Arkansas, on the other hand, have lands in excess.

VALLEY IRRIGATION MAINLY FROM WELLS.

The valley lands will be irrigable less because they are near stream level than because they lie close to the ground water. Even along valley bottoms irrigation will be mainly from wells. This is especially true of the spring-stream valleys, of which the Cimarron is a good example. Flow in the typical spring-stream valley is perennial, where there is flow at all; but it is characteristically interrupted, sinking and reappearing, the dry lengths being usually much the longer. In these dry lengths the depth to the ground-water level is still comparatively slight, and irrigation is practicable from wells. It is true in large part also of the mountain streams, because they have intermittent flow, the dry period, or at least the period of enfeeblement, coinciding with the crop-growing season. And it becomes true of these streams especially where irrigation to the westward exhausts their flow in that season, as in the case of the Arkansas along its rather broad bottom from the Colorado-Kansas line to Garden.

The valley of the Canadian, measured across between its upland margins, is the broadest—20 miles or more. But because deep also, and therefore sharply eroded, it has an insignificant total of cultivable and irrigable land. The Arkansas valley, on the other hand, is comparatively narrow and shallow; but its proportion of good land is large and lies close to the water plane, with a great depth of unconsoli-

dated sand and gravel beneath. This is the case with nearly all the spring-stream valleys. They are sunk, as a rule, approximately to the ground-water level, and are there broadened. But they have much more of flat bottom land than is irrigable from their streams, and, for its fullest utilization, recourse must be had to the ground water.

Upon the uplands the ground water proves to be a practicable source of supply for the watering of stock, at pumping lifts reaching even to 300 feet; that is, the diminutive stream obtainable by windmill power from such depths nevertheless is sufficient for the purposes of the stockman. The volume of discharge diminishes as the height of lift increases. What the economical limit will be in irrigation will depend upon the value of the product. Valley irrigation on the High Plains will not pay, as a rule, until a pastoral population, scattered over the intervalley areas, shall have created a local market. It would not pay at present, for example, in the valley of the Upper Beaver; yet eventually a considerable acreage of bottom land there will have a strictly agricultural population occupied in supplying garden and orchard products to the upland stockmen.

The town of Garden, situated on a railroad, is thereby afforded opportunity to compete in a distant market. The economical pumping limit at Garden, under present conditions, can hardly be said to reach 20 feet. Under the more favorable conditions of future development and a local market this will probably not be increased by more than 50 per cent. That is, 25 feet appears to be about the limit of height above the water plane at which irrigation farming from wells can profitably be conducted—at least on a commercial basis. During the early years of irrigation a notable area of bottom land here, though an inconsiderable portion of the whole, was converted from bare grass land into a veritable garden by ditch diversion from the river. It was owing to the nature of this early conspicuous success in reclamation that the town received its name. However, subsequent development of like character to the westward, in Colorado, resulted in such large drafts upon the river there as eventually to leave it dry in Kansas.

After a period of puzzled inaction, discovery of "the underflow" having meantime been made, recourse was had to windmill pumping from the ground water. Pl. LXV shows the number and the distribution of these pumping wells up to 1899. In that year the area under irrigation by this means very nearly equaled that formerly served from the river. The number of wells is increasing, and the town has been restored practically to its former prosperous condition.

A considerable remaining area here, as with similar tracts in other valleys, awaits the stimulus to development of a local market, which will be the outcome of a systematically distributed pastoral population upon the uplands.

IMPORTANCE OF CORRECT WELL CONSTRUCTION.

The assumption is here made that wells are so constructed that the water level is not materially drawn down, and the lift increased, under ordinary pumping. Few wells are in fact so constructed. Yet, under conditions which almost universally obtain upon the High Plains and in many of the valleys, viz, of deep alluvium, deep in water, nearly all might be. Thus there is a problem of the well, no less important than that of the lifting mechanism. Only this mechanism of pump and wind wheel, or other power device, has so far, however, been made the subject of careful study, in the effort to secure the maximum of well delivery.

Both upon the uplands, for stock watering, and in the valleys, for irrigation, the greater number of wells fall short of their possibilities. Many wells, owing to unintelligent construction, absolutely fail—i. e., are quickly drawn down to the bottom, or temporarily "exhausted," by pumping—where, with slightly increased outlay, full delivery might have been secured. In stock watering, so far, the needs have appeared to be within the possibilities of the average well, so appreciative has the stockman been of even a bare drinking supply in the desert spaces. But in time he will come to recognize that an excess over apparent requirements is necessary in order to avoid stagnation and too high a temperature in summer and freezing in winter. In irrigation, on the other hand, the well at its best falls short of the demands that could profitably be made upon it. It is in areas "shallow to water," therefore, that the differences among wells, in respect to their rates of response to pumping, are conspicuous.

The well for irrigation serves a small area. At Garden there are 102 wells within 1 square mile of valley bottom. Upon the uplands a single well is equal to the stock-watering needs of half a dozen square miles of grazing land. The depth to water in the effective wells about Garden, as we have seen, does not exceed 20 feet, while in the upland wells it ranges down to 300 feet. The problem in each case, however, is the same—namely, to secure a rate of response to maximum pumping sufficiently rapid to prevent serious increase of the pumping lift.

Not only must valley irrigation in the future largely depend upon pumping from the ground water, but it will be solely by means of wells also that the great intervalley uplands will be reclaimed, even to pastoral uses; and while the mechanical processes of well making upon these elevated flats must necessarily differ somewhat from those employed in the valleys, because of the great difference in the depth to water, the principles of well construction in each case, so far as they relate to the intake of water, are the same. Thus the determination of principles and the working out of the best type of construction are of importance to uplands and valleys alike.